NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2709

FATIGUE AND STATIC TESTS OF FLUSH-RIVETED JOINTS

By Darnley M. Howard and Frank C. Smith

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SUMMARY

Fatigue tests at zero mean load were made on 190 multiple-rivet joints having 1/8-inch-diameter A17S-T3 100° countersunk-head rivets. Some of the joints had machine-countersunk holes and some had dimpled holes. The joints had three rivets at 1-inch pitch or six rivets at 1/2-inch pitch. Both butt and lap joints were tested. Static tests were made on 34 typical joints. The sheet materials used were 0.032-inch-thick bare and alclad 75S-T6 sheet, 0.032-inch-thick bare and alclad 24S-T3 sheet, and 0.064-inch-thick alclad 75S-T6 sheet.

Joints made by dimpling showed marked superiority in both fatigue and static strengths to those made by machine countersinking. Joints of alclad sheets using machine-countersunk holes had greater fatigue strength than similar joints of bare sheets. Lap and butt joints, using machine-countersunk holes, had nearly equal strength under static loads; while the lap joints were superior under fatigue loads.

A photomicrograph of an 0.032-inch lap joint of alclad 24S-T3 sheet using machine-countersunk holes, tested at a load slightly over that needed to cause a permanent slip of 4 percent of the rivet hole diameter, showed substantial gouging of the rivet by the sharp edge of the sheet. Another photomicrograph of a dimpled joint of 75S-T6 sheet showed that the fatigue cracks tended to propagate through heavily cold-worked material.

The relationships between measured static properties of lap joints and fatigue life for the four materials are given. No satisfactory single relation between static properties and fatigue life covering the four materials could be found.

INTRODUCTION

A large amount of work has been done on the fatigue strength of riveted joints. A comprehensive list of references to work done prior to 1946 is given by Jackson, Grover, and McMaster on page 154 of reference 1. They state, "Many investigators have found that machine-countersunk rivets produce weaker joints than plain dimpled or press-countersunk riveted joints."

More recent work on the fatigue strength of riveted joints is described in references 2, 3, and 4. Reference 2 gives the results of tests to show the effects of notches, type of joint, temperature, material, joint configuration, and ratio of maximum to minimum stress on the fatigue life. Reference 3 gives fatigue test results with completely reversed stresses for joints using single 3/16-inch-diameter 24S-T31 rivets in a variety of sheet materials. No one sheet alloy shows consistent superiority in the tests of reference 3, though alclad 24S-T3 is generally on the high side of the group. The design of the joint is found in reference 3 to have a greater effect on the range of fatigue strengths than does the choice of sheet material. Reference 4 gives the results of Swedish fatigue tests using fluctuating tensile stress on joints of several different configurations. Here again there is no consistent superiority for any one sheet material.

A study of the effect of a central drilled hole on the fatigue properties of 24S-T3 and 75S-T6 aluminum-alloy strips at zero mean stress was the first part of the present investigation (reference 5). The present report extends this work to fatigue and static tests of flush-riveted joints of both butt and lap types.

The results presented give additional information on the strength of riveted joints as follows:

(1) The loads are sufficiently high to give some failures well below 10,000 cycles

(2) The tests were conducted with completely reversed load using lateral guides to prevent buckling during the compressive portion of the load cycle

(3) An attempt is made to correlate the fatigue strength with static-slip strengths

(4) Similar joints are tested in 0.032-inch bare and alclad 24S-T3 and 75S-T6 aluminum-alloy sheet for comparison purposes

Mr. William C. Brueggeman, formerly of the National Bureau of Standards, developed the testing technique and conducted most of the tests in the cycle range above 10,000 cycles.

This investigation was conducted at the National Bureau of Standards and has been made available to the National Advisory Committee for

Aeronautics for publication because of its general interest. The authors are indebted to the Bureau of Aeronautics for permission to publish this work.

SPECIMENS

The construction of the fatigue test specimens is shown in figure 1. These specimens were multiple-rivet joints 3 inches wide. In the case of the butt joints (fig. 1(a)) each of the two abutting sheets was joined by a row of rivets to a third sheet of 24S-T3 aluminum alloy 0.125 inch thick. In the case of the lap joints (fig. 1(b)) the overlapping sheet was allowed to extend 2.75 inches to either side of the rivet line to simplify the use of lubricated solid guides which will be described in a subsequent section of this report.

The sheet materials used were 0.032-inch-thick bare and alclad 75S-T6 sheet, 0.032-inch-thick bare and alclad 24S-T3 sheet, and 0.064-inch-thick alclad 75S-T6 sheet. All of the joints used 1/8-inch A17S-T3 aluminum-alloy rivets with 100° countersunk heads. In some of the joints machine-countersunk holes were used; in the rest, dimpled holes were formed using the dimpling fixture shown in figure 2. All riveting and dimpling were done on the Cleveland Pneumatic Tool Company model 24B pedestal squeezer. The diameter of the driven head was made equal to approximately 1.5 times the nominal shank diameter. None of the driven heads showed cracks.

Tests to determine axial-load S-N curves of the sheet material were not made since previous tests showed no correlation between the fatigue strength of joints and that of the sheet material from which they were fabricated.

The static tensile and compressive properties of the sheet materials are given in table 1. The shearing strength of the rivets was taken as that given in reference 2, 32.0 kips per square inch.

TESTS

All the fatigue tests were conducted under completely reversed axial load in a modified Templin fatigue testing machine at 2000 cycles per minute. Lubricated wooden guides similar to those shown in figure 3 restrained the specimen from buckling during the compression half of the load cycle. The guide shown in figure 3 was designed to restrain the specimens tested in the low cycle range. The guide shown in figure 4 was used for the tests in the high cycle range but was found inadequate in the low cycle range where the loads spread it apart. The technique was identical for both types of guides. Greased paper was used between guide and specimen as described in reference 6. In the lap-joint tests, greased paper was also inserted under the extended tabs of the joint (fig. 1(b)) to within about 1 inch of the rivet line. This paper reduced transfer of load by friction at these tabs. The tightness of the guide on the specimen was such that the guide could be slid axially by hand. A different guide-block design was used for lap and butt joints so that the length of unsupported specimen near the rivets was small. The guides effectively prevented buckling of the specimen.

For tests at loads that produced failure at less than 10,000 cycles, the set of grips shown at A (fig. 3) was used. These grips were made of hot-rolled steel with transversely serrated contact surfaces. Three tightening screws were used. An earlier form of grip using two tightening screws was used for the tests at low and moderate loads.

The constancy of load of the Templin fatigue machine at loads high enough to cause some permanent slip in the joints was investigated because of the nature of the machine construction. In this machine, the dynamometer A (fig. 4) is loaded by the specimen B, which in turn is loaded by the Scotch yoke C. In normal operation, nearly all of the motion of the Scotch yoke is used in stretching the dynamometer ring A, thus giving a loading condition which is relatively insensitive to small changes in specimen stiffness. With riveted-joint specimens tested at loads high enough to cause appreciable slip, however, there was some question regarding the constancy of the load as the test progressed. For this reason, the load-cycles curves shown in figure 5 were determined for two typical specimens. One of these, specimen A, had an initial load slightly in excess of that required to produce a static slip of 4 percent of the rivet hole diameter; the other, specimen B, had a load slightly below the 4-percent-slip value. The testing machine was stopped periodically and the tensile and compressive peak loads were measured. For specimen A, the average load had dropped 12 percent at 1230 cycles; for specimen B, the average load had dropped 4 percent at 800 cycles and had risen 2 percent at 5000 cycles. On the basis of these results it was concluded that the testing machine would adequately maintain loads up to the 4-percent-slip value to failure.

Elongation of the rivet holes and "cupping" of the rivet heads (fig. 6) occurred during failure of some of the dimpled joints. When this type of failure was obtained the number of cycles at failure was taken as the number at which the cut-off relay for stopping the machine was actuated. This relay functioned before the load could drop more than 7 percent. It was assumed that this tearing failure, once started, progressed rapidly and that consequently the load was fully maintained during the major portion of the test.

Static tests were made on each type of joint to determine the maximum load and the relation between applied load and the resulting slip or permanent displacement of the joined pieces. A continuous reference line was scribed with a razor blade on the edges of the overlapping sheets on each side of the joint. The slip was determined by applying a load, unloading to zero, measuring the amount of offset in the reference line by means of a Brinell microscope, applying a greater load, unloading, and so forth. The amount of slip determined on the two edges was averaged. In the case of butt joints, the slip was measured between each sheet and the backing strip, resulting in two sets of load-slip data for each specimen. In most cases joints having six rivets at 1/2-inch pitch were used for these static tests; however, in some cases the joints had three rivets at 1-inch pitch. Joints having fewer than six rivets were used in some of the tests since it was found in other tests of riveted joints that variation of rivet pitch above 3/8 inch has no great effect on the static load per rivet corresponding to a given amount of slip.

RESULTS

Typical static load-slip curves for joints of the type tested are shown in figure 7. The loads per rivet for each of the 34 joints subjected to static tests are given in table 2 for slips of 2, 4, and 6 percent of the rivet hole diameter. In addition, the maximum loads are given in this table. For a given type of joint, 75S-T6 sheet, bare and clad, gave more strength than 24S-T3, bare and clad. For a given sheet material, joints using dimpled holes were much stronger than those using machine-countersunk holes. Lap and butt joints, using machine-countersunk holes, had nearly equal strength under static loads.

Fatigue tests at zero mean load were made on 190 multiple-rivet joints. The types of joints for which the fatigue tests were made and the number of tests of each type are listed in table 3. The curves of load per rivet against cycles to failure are given in figures 8, 9, and 10. The average load for a slip of 4 percent of the rivet hole diameter and the maximum static load, as given in table 2, are shown in each figure. A scale obtained by dividing the fatigue load amplitude by the average maximum static load per rivet as given in table 2 is also shown on the right side of each figure. The results show that joints of alclad sheets using machine-countersunk holes had greater fatigue strength than similar joints of bare sheets. Also, comparison of the lap and butt joints using machine-countersunk holes shows that the lap joints were superior under fatigue loads.

The curves faired through the data of figures 9 and 10 (lap joints) are repeated in figure 11 for comparison with each other. It is evident that for 0.032-inch sheet joints using dimpled holes are markedly superior to those using machine-countersunk holes.

To illustrate the behavior of the two types of lap joints, machine-countersunk and dimpled, in terms of the static properties measured, figures 12(a) and 12(b) were prepared. Figure 12(a) shows the curve of ratio of fatigue to static strength against cycles to failure for machine-countersunk rivets in four materials while figure 12(b) shows the same relation for dimpled joints of the same materials. Each material in each graph has a characteristic curve which, while similar to those of the other materials, is vertically displaced. Figure 11 shows the curves of load against cycles to failure for these joints. The 0.032-inch dimpled joints of the four materials, for example, fall in a reasonably narrow band indicating that they have nominally the same fatigue strength.

It appears that the vertical displacements of the curves of figures 12(a) and 12(b) are due to differences in static properties of the joints appearing as a constant in the fatigue strength ratios. It is further noted that the differences in materials have more effect on the statically loaded joints than on those loaded in fatigue. On the basis of ultimate load and type of joint the best single relation, covering the four materials, between load and cycles to failure can be made on the basis of actual fatigue load on the rivet without regard to the static ultimate strength of the joint.

The mode of failure varied for the different types of joints. All the joints using machine-countersunk holes in 0.064-inch sheet failed by rivet shear. The joints using machine-countersunk holes in 0.032-inch sheet failed by rivet shear at the higher loads and through the sheet at the lower loads. The joints using dimpled holes in 0.032-inch sheet failed through the sheet at low and moderate loads and failed by an elongation and tearing of the sheet at the rivet holes accompanied by cupping of the rivet heads at high loads.

Figures 13(a) and 13(b) are photomicrographs of the left and right sides of a rivet in an 0.032-inch-thick alclad 24S-T3 aluminum-alloy lap joint with machine-countersunk holes. Photomicrographs of a similar joint after it had been subjected to 200 cycles of completely reversed load slightly above the 4-percent static-slip value are shown in figures 14(a) and 14(b). The fatigue loading caused gouging of the rivet, tipping of the rivet head, and deformation of the sharp edge of the upper plate.

Figure 15 is a photomicrograph of typical 75S-T6 aluminum-alloy dimpled joints after fatigue failure. The deformation of the sheets and rivets due to cold-working during fabrication is clearly shown. It is interesting to note that the rivets do not appear to fill the holes completely in these joints. The damaged area at A (fig. 15) is shown much enlarged in figure 16. The crack began apparently at the point of highest cold-work B (fig. 16) and initially propagated in the direction of the slip lines. A secondary crack on the convex side of the sheet may have affected the direction of propagation as the failure progressed. A similar crack in another joint is shown in figure 17.

CONCLUSIONS

Fatigue and static tests were made of 1/8-inch-diameter A17S-T3 100° countersunk-head rivets in lap and butt joints. Both machine-countersunk and dimpled holes were used. The sheet materials were 0.032-inch-thick bare and alclad 24S-T3 and 75S-T6 aluminum alloys and 0.064-inch-thick alclad 75S-T6 alloy. From the results the following conclusions may be drawn:

1. Flush-riveted joints using dimpled holes have greater strength than those using machine-countersunk holes under both static and fatigue loads.

2. Lap and butt joints, using machine-countersunk holes, have nearly equal strength under static loads; while the lap joints are superior under fatigue loads.

3. Joints of alclad sheets using machine-countersunk holes have greater fatigue strength than similar joints of bare sheets.

4. The mode of fatigue failure of joints changes with the type of joint from failure by rivet shear, for 0.064-inch sheet using machine-countersunk holes, to failure by elongation and tearing of the sheet at the rivet holes accompanied by cupping of the rivet heads for dimpled joints at high loads.

5. The direction of fatigue cracks is largely influenced by the direction of slip lines in heavily cold-worked areas of dimples.

6. Although curves are shown relating cycles to failure with the static properties - ultimate strength and load for 4-percent slip - for 0.032-inch lap joints of the four materials, no satisfactory single relation covering the four materials was found for predicting the behavior of a type of joint from the static properties of a similar joint of the same material.

National Bureau of Standards
Washington, D. C., October 24, 1951

REFERENCES

1. Jackson, L. R., Grover, H. J., and McMaster, R. C.: Advisory Report on Fatigue Properties of Aircraft Materials and Structures. OSRD No. 6600, Ser. No. M-653, War Metallurgy Div., NDRC, March 1, 1946.

2. Russell, H. W., Jackson, L. R., Grover, H. J., and Beaver, W. W.: Fatigue Strength and Related Characteristics of Aircraft Joints. II - Fatigue Characteristics of Sheet and Riveted Joints of 0.040-Inch 24S-T, 75S-T, and R303-T275 Aluminum Alloys. NACA TN 1485, 1948.

3. Holt, Marshall: Results of Shear Fatigue Tests of Joints with 3/16-Inch-Diameter 24S-T31 Rivets in 0.064-Inch-Thick Alclad Sheet.. NACA TN 2012, 1950.

4. Lundberg, Bo K. O., and Wållgren, Gunnar G. E.: A Study of Some Factors Affecting the Fatigue Life of Aircraft Parts with Application to Structural Elements of 24S-T and 75S-T Aluminum Alloys. Meddelande nr 30, Flygtekniska Försöksanstalten (Stockholm), 1949.

5. Brueggeman, W. C., and Mayer, M., Jr.: Axial Fatigue Tests at Zero Mean Stress of 24S-T and 75S-T Aluminum-Alloy Strips with a Circular Hole. NACA TN 1611, 1948.

6. Brueggeman, W. C., and Mayer, M., Jr.: Guides for Preventing Buckling in Axial Fatigue Tests of Thin Sheet-Metal Specimens. NACA TN 931, 1944.

TABLE 1.- MECHANICAL PROPERTIES OF MATERIALS USED IN JOINTS

Material	Thickness (in.)	Tensile properties			Compressive properties	
		Yield strength (psi) (1)	Young's modulus (psi)	Ultimate strength (psi)	Yield strength (psi) (1)	Young's modulus (psi)
75S-T6 alclad	0.032	72.0×10^3	10.4×10^6	78.6×10^3	63.6×10^3	10.1×10^6
75S-T6 alclad	.064	75.0	10.1	83.0	69.5	10.3
24S-T3 bare	.032	56.0	10.5	73.5	47.0	10.9
24S-T3 alclad	.032	49.5	10.0	67.4	46.0	10.6
75S-T6 bare	.032	74.0	10.7	83.7	69.0	10.9

[1]At 0.2-percent offset.

TABLE 2.- STATIC PROPERTIES OF FLUSH-RIVETED JOINTS IN PLATES 3 INCHES WIDE WITH A17S-T3 RIVETS

Type of joint (a)	Sheet thickness (in.)	Sheet material	Specimen	Number of rivets (b)	Load (lb) per rivet at slip[c] (percent) of -			Maximum load per rivet (lb)
					2	4	6	
MC-butt	0.032	75S-T6 alclad	1	6	[d]138	[d]160	[d]187	422
			2	6	[d]106	[d]116	[d]154	373
			Average		[d]122	[d]138	[d]170	398
MC-butt	0.064	75S-T6 alclad	3	6	[d]322	[d]346	[d]360	400
			4	6	[d]226	[d]341	[d]377	406
			Average		[d]274	[d]343	[d]368	403
MC-lap	0.032	75S-T6 alclad	5	3	135	184	229	413
			6	3	159	200	239	403
			7	6	123	189	216	383
			Average		139	191	228	400
MC-lap	0.032	75S-T6 bare	8	3	149	200	228	320
			9	3	140	172	195	411
			10	6	129	189	216	321
			11	6	132	189	217	396
			Average		138	188	214	362
MC-lap	0.032	24S-T3 alclad	12	6	81	150	188	323
			13	6	153	186	205	319
			Average		117	168	197	321
MC-lap	0.032	24S-T3 bare	14	3	120	145	171	333
			15	3	155	180	205	380
			Average		138	163	188	356
MC-lap	0.064	75S-T6 alclad	16	3	320	350	373	409
			17	6	316	356	376	425
			18	6	312	348	367	413
			Average		316	351	372	416
D-lap	0.032	75S-T6 alclad	19	3	392	493	530	569
			20	3	353	430	465	540
			21	6	350	452	489	554
			22	6	346	453	489	527
			Average		360	457	493	548
D-lap	0.032	75S-T6 bare	23	3	372	440	451	480
			24	3	317	400	459	480
			25	6	367	413	439	460
			26	6	317	388	434	465
			Average		343	410	446	471
D-lap	0.032	24S-T3 alclad	27	3	300	367	393	468
			28	3	278	353	390	453
			29	6	297	345	413	507
			30	6	312	364	386	424
			Average		297	357	396	463
D-lap	0.032	24S-T3 bare	31	3	320	355	372	400
			32	3	338	381	382	437
			33	6	325	355	379	400
			34	6	308	355	374	395
			Average		323	362	377	408

[a]MC-butt, butt joint using machine-countersunk holes; MC-lap, lap joint using machine-countersunk holes; D-lap, lap joint using coin-dimpled holes.

[b]Joints with six rivets had 1/2-inch pitch; joints with three rivets had 1-inch pitch.

[c]Slip is given in percentage of rivet hole diameter (0.1285 in.).

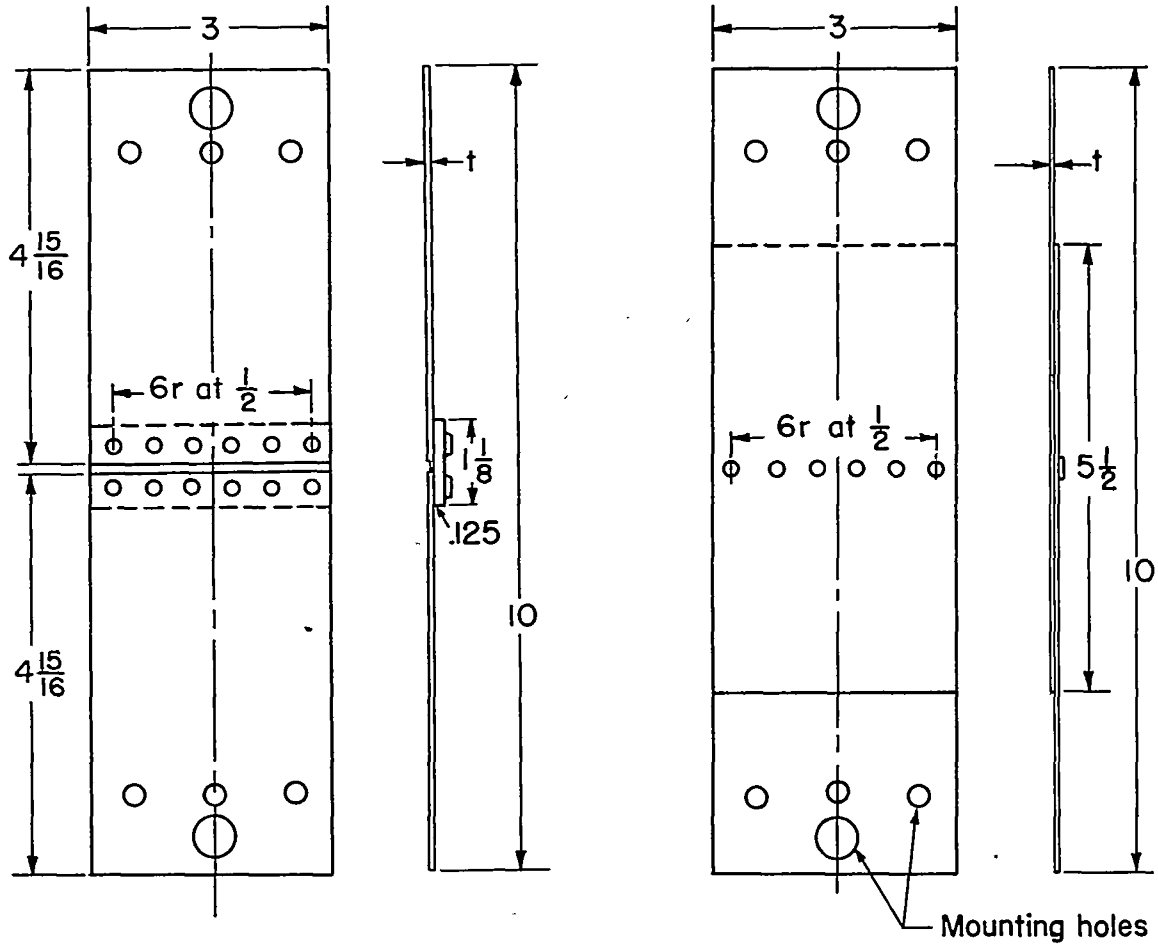
[d]Values obtained by averaging the two sets of slip data obtained on each butt joint.

TABLE 3.- DESCRIPTION OF FATIGUE TESTS OF FLUSH-RIVETED JOINTS IN PLATES 3 INCHES WIDE WITH A17S-T3 RIVETS

Type of joint (a)	Sheet thickness (in.)	Sheet material	Number of joints tested	Lowest number of cycles to failure	Highest number of cycles to failure
MC-butt	0.032	75S-T6 alclad	15	2000	3,108,000
MC-butt	.064	75S-T6 alclad	23	20	[b]7,959,000
MC-lap	.032	75S-T6 alclad	16	800	10,608,200
MC-lap	.032	75S-T6 bare	25	400	9,170,300
MC-lap	.032	24S-T3 alclad	15	200	10,752,000
MC-lap	.032	24S-T3 bare	18	2000	5,565,800
MC-lap	.064	75S-T6 alclad	21	500	[b]11,666,500
D-lap	.032	75S-T6 alclad	12	130	108,600
D-lap	.032	75S-T6 bare	11	290	95,400
D-lap	.032	24S-T3 alclad	22	101	2,149,700
D-lap	.032	24S-T3 bare	12	287	[b]10,000,000

[a]MC-butt, butt joint using machine-countersunk holes; MC-lap, lap joint using machine-countersunk holes; D-lap, lap joint using coin-dimpled holes.

[b]Removed before failure.



(a) Butt joint. (b) Lap joint.

Figure 1.- Riveted-joint specimens. All dimensions in inches. (For some tests three rivets at 1-inch pitch were used. For low-load tests only two mounting holes were needed for the grip used.)

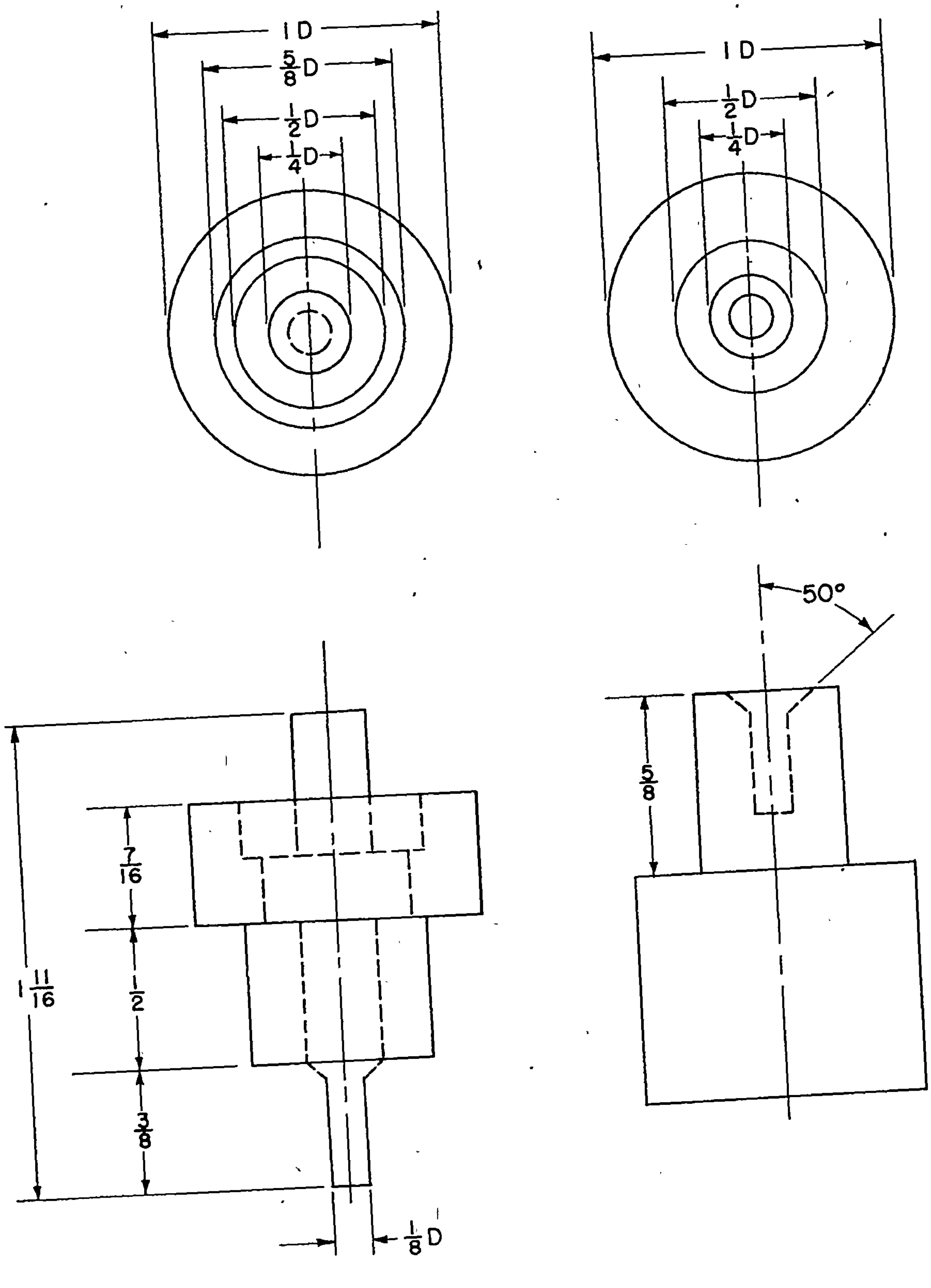


Figure 2.- Dimpling fixture. All dimensions in inches.

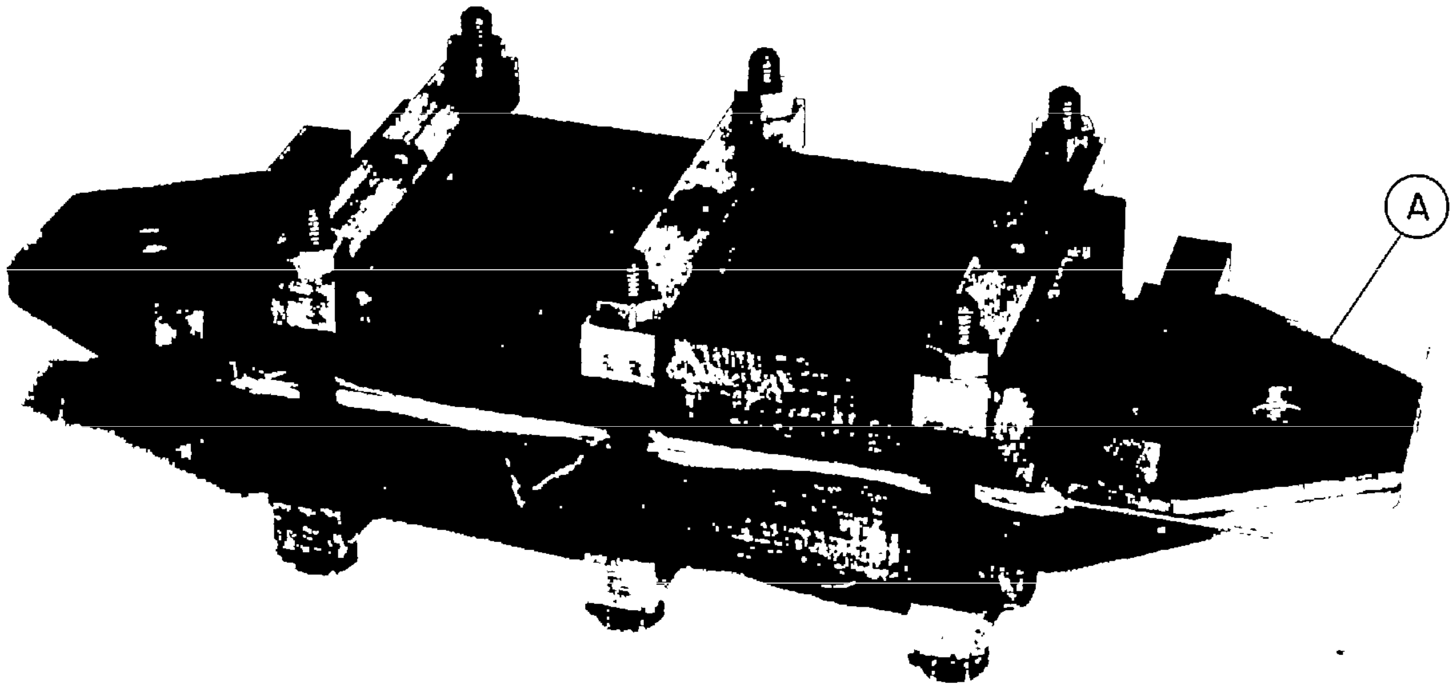


Figure 3.- 0.032-inch lap-joint fatigue specimen ready for test. A, grips.

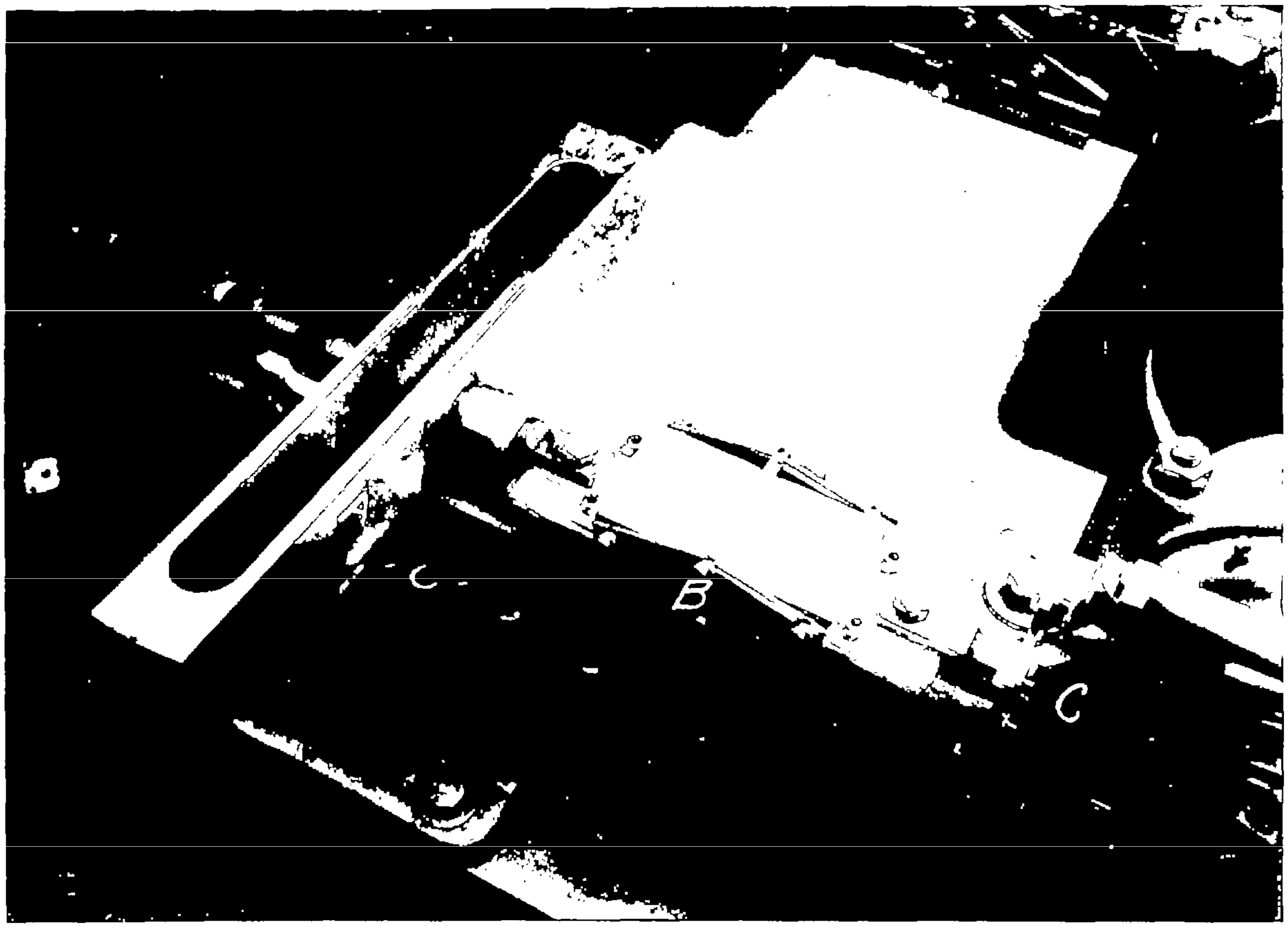


Figure 4.- Templin fatigue machine. A, dynamometer; B, specimen;
C, Scotch yoke.

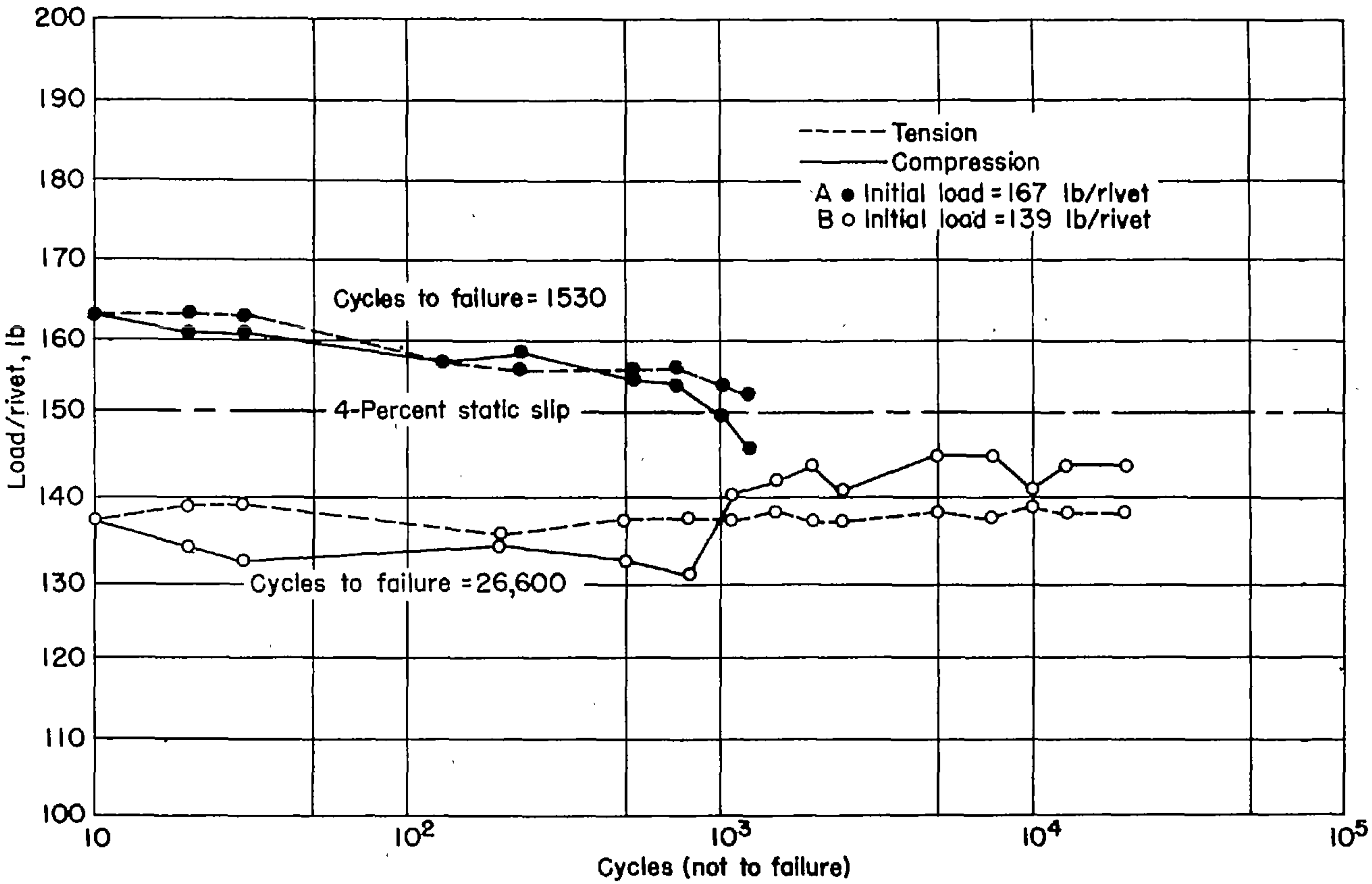


Figure 5.- Load-cycle curve showing consistency of loading during tests of two 0.032-inch alclad 24S-T3 countersunk lap joints.

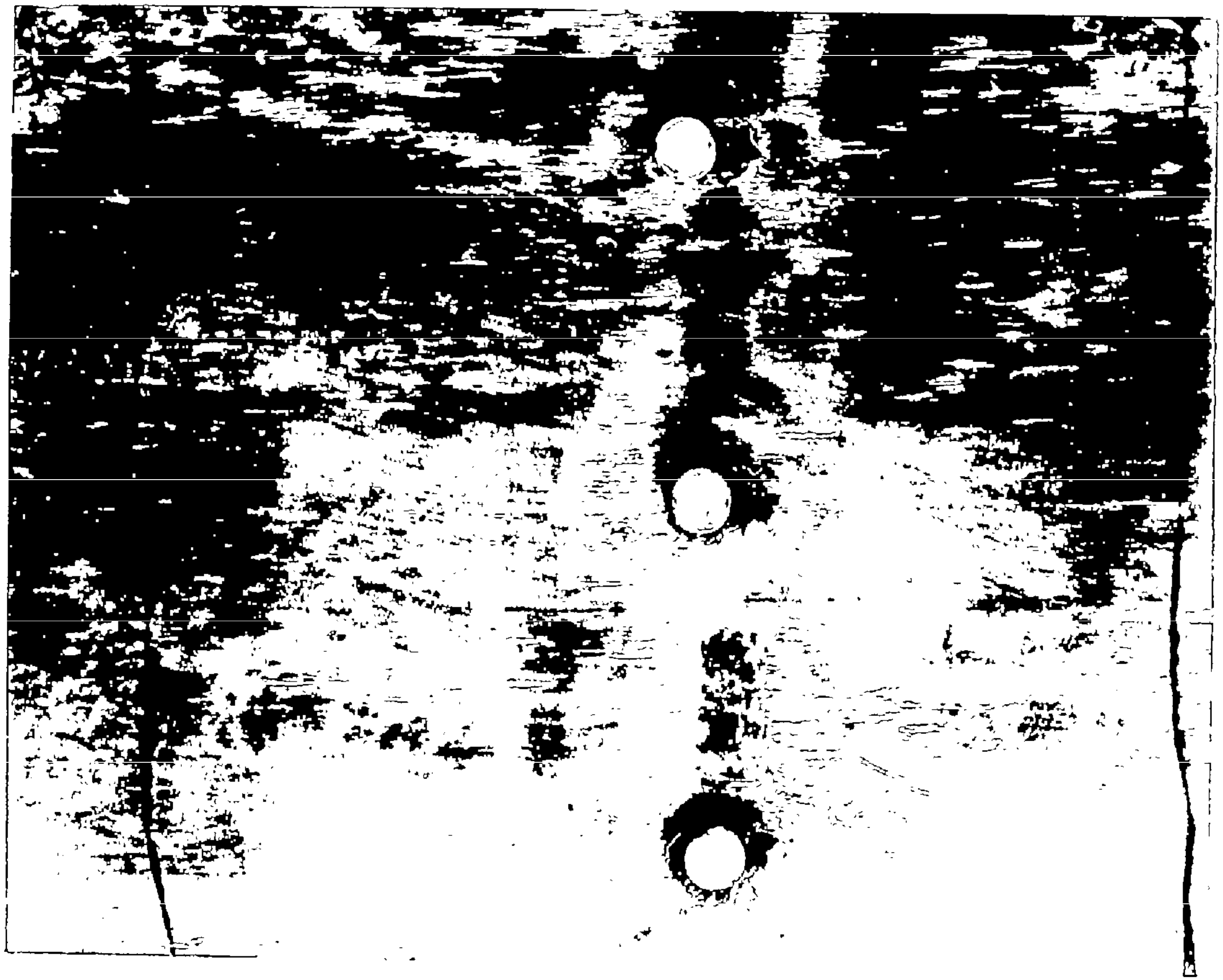


Figure 6.- Riveted joint that failed by rivet hole elongation.

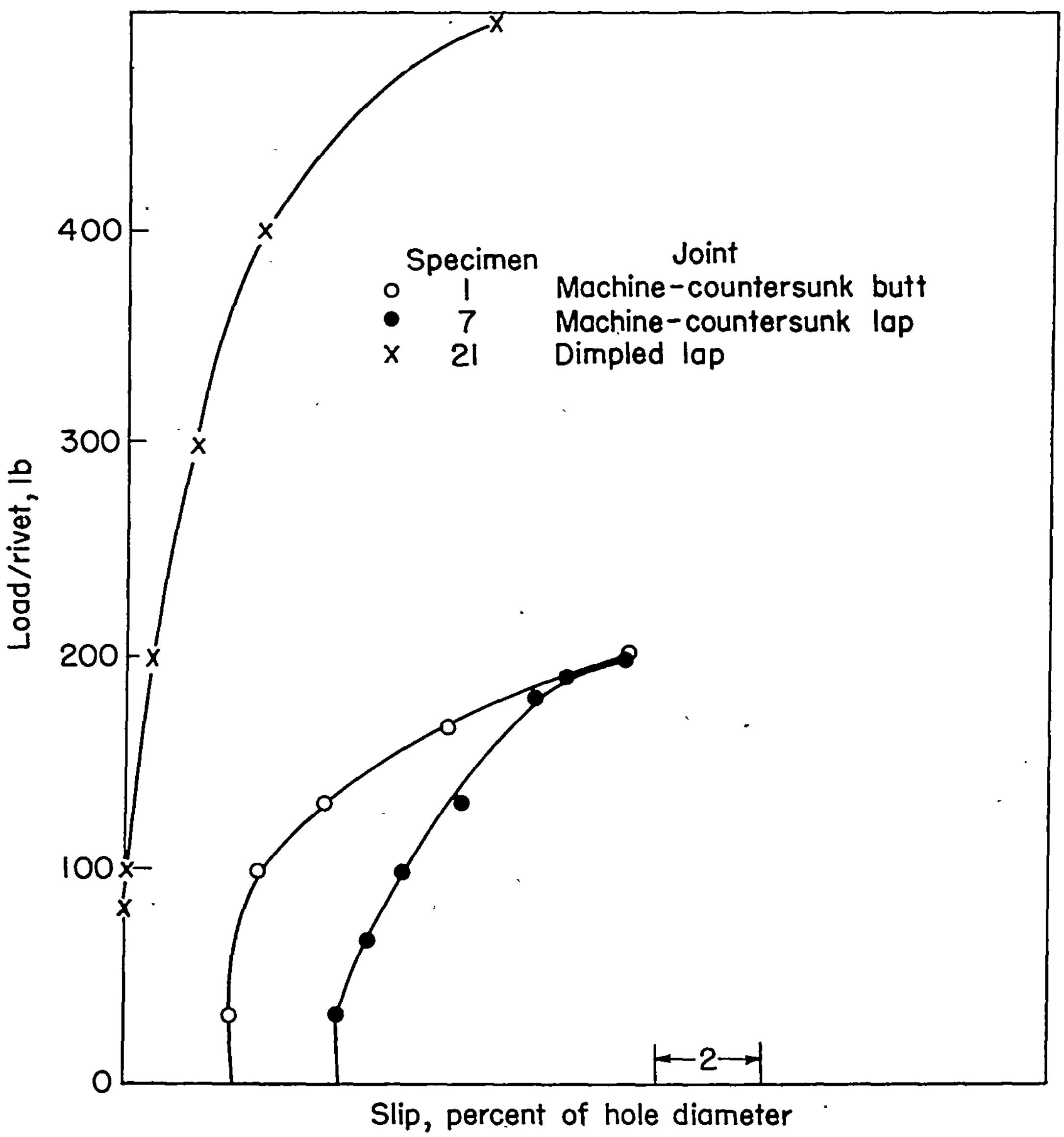
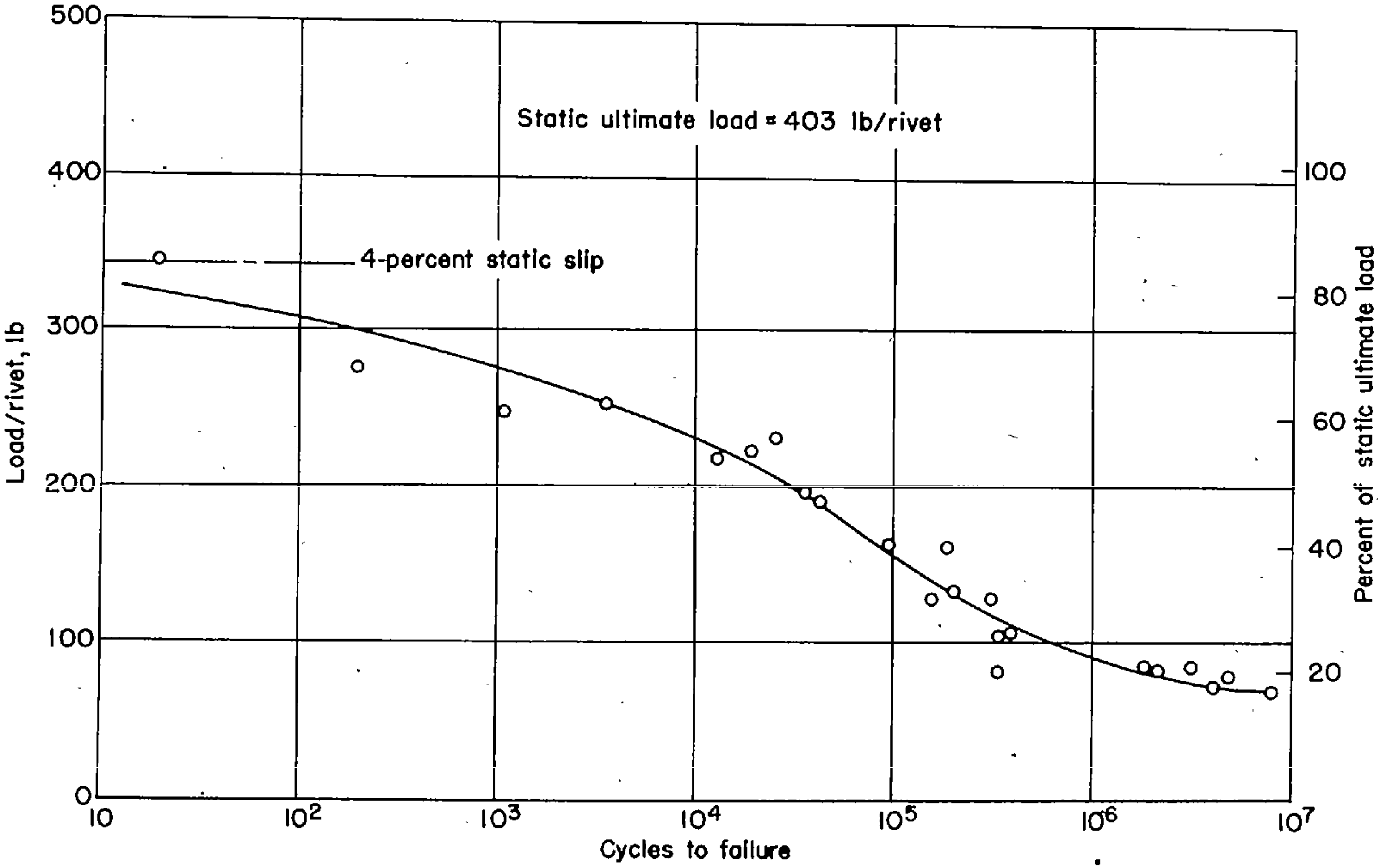
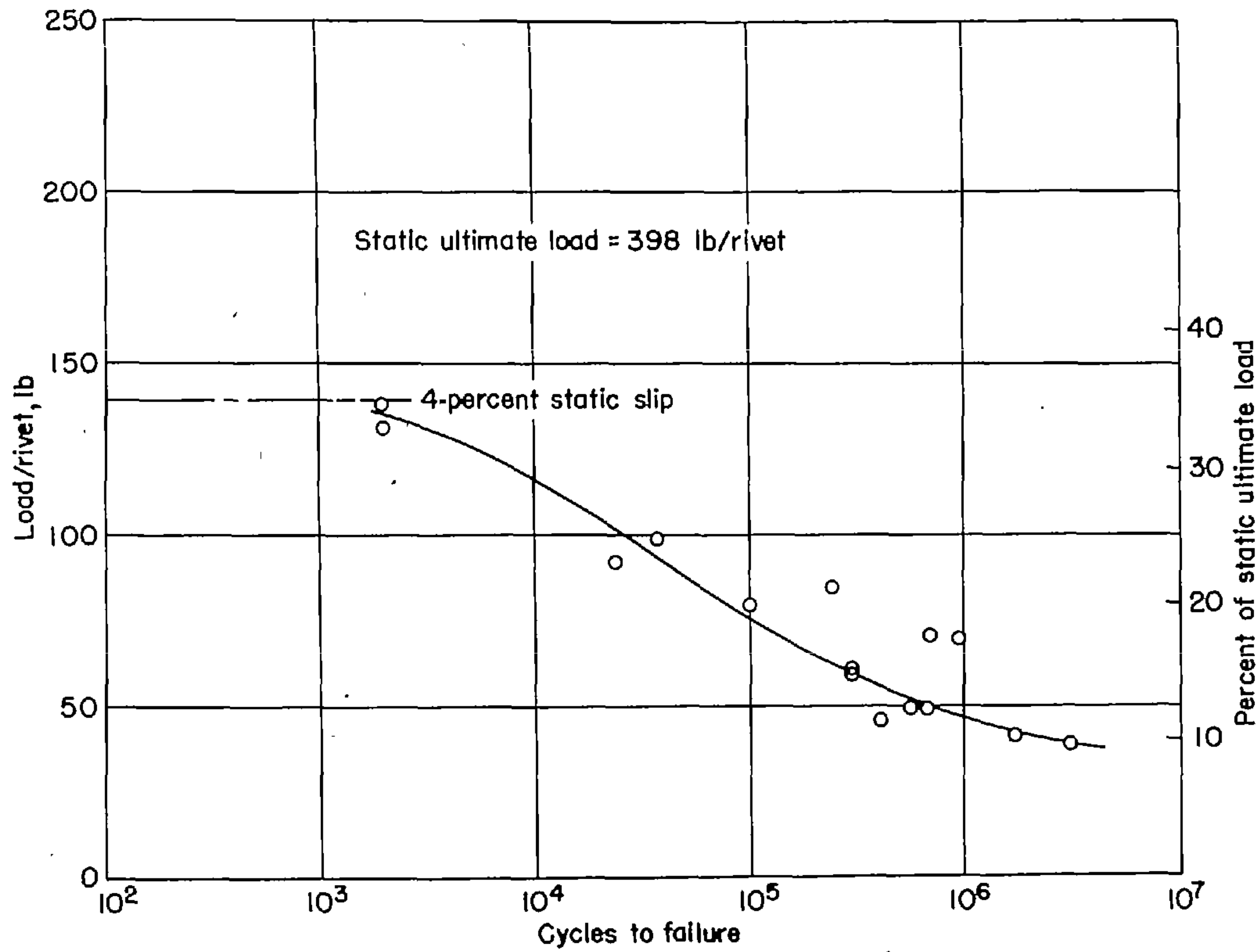


Figure 7.- Typical static load-slip curves of 0.032-inch alclad 75S-T6.



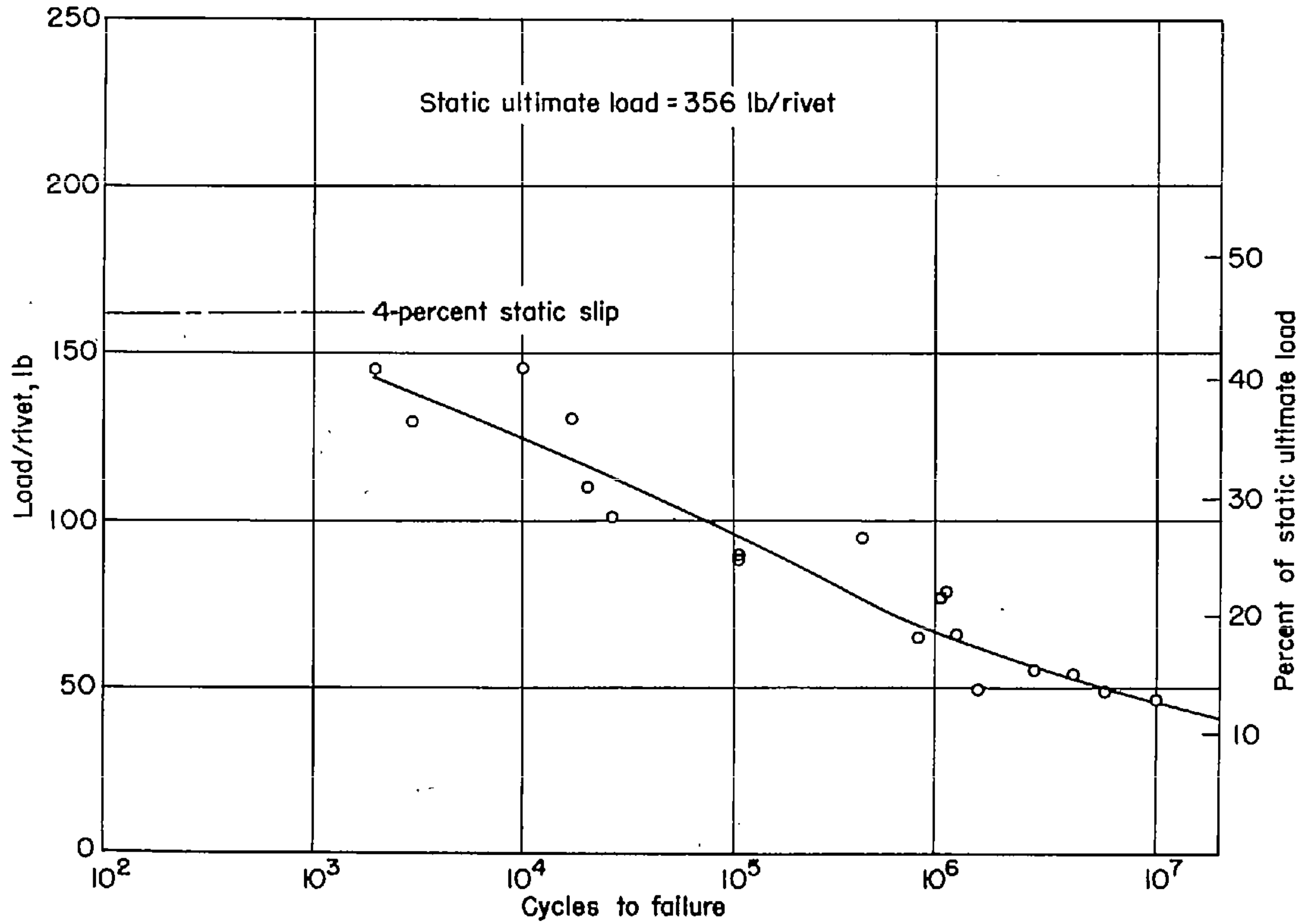
(a) 0.064-inch alclad 75S-T6.

Figure 8.- Curves of load per rivet against cycles to failure for machine-countersunk butt joints.



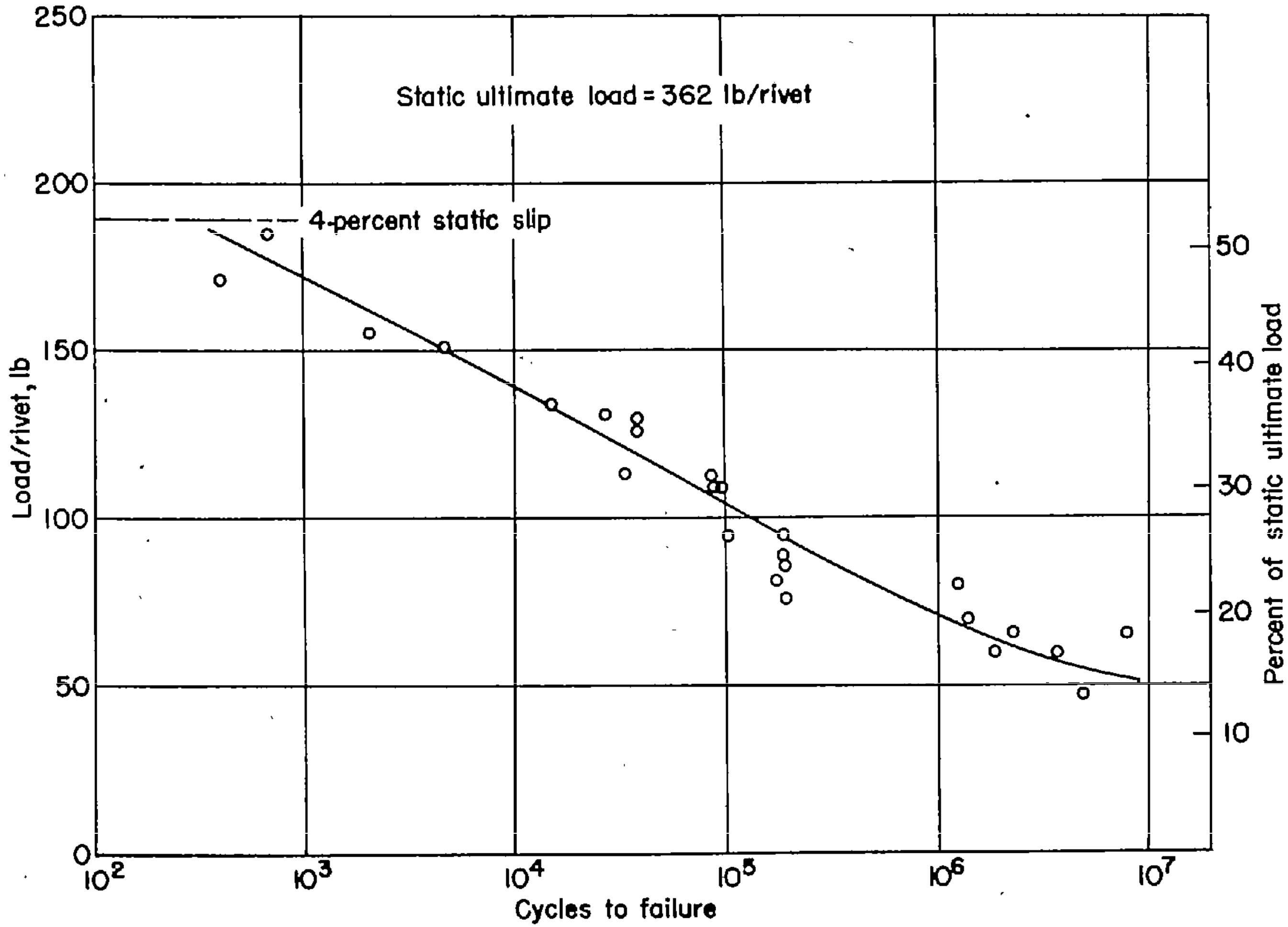
(b) 0.032-inch alclad 75S-T6.

Figure 8.- Concluded.



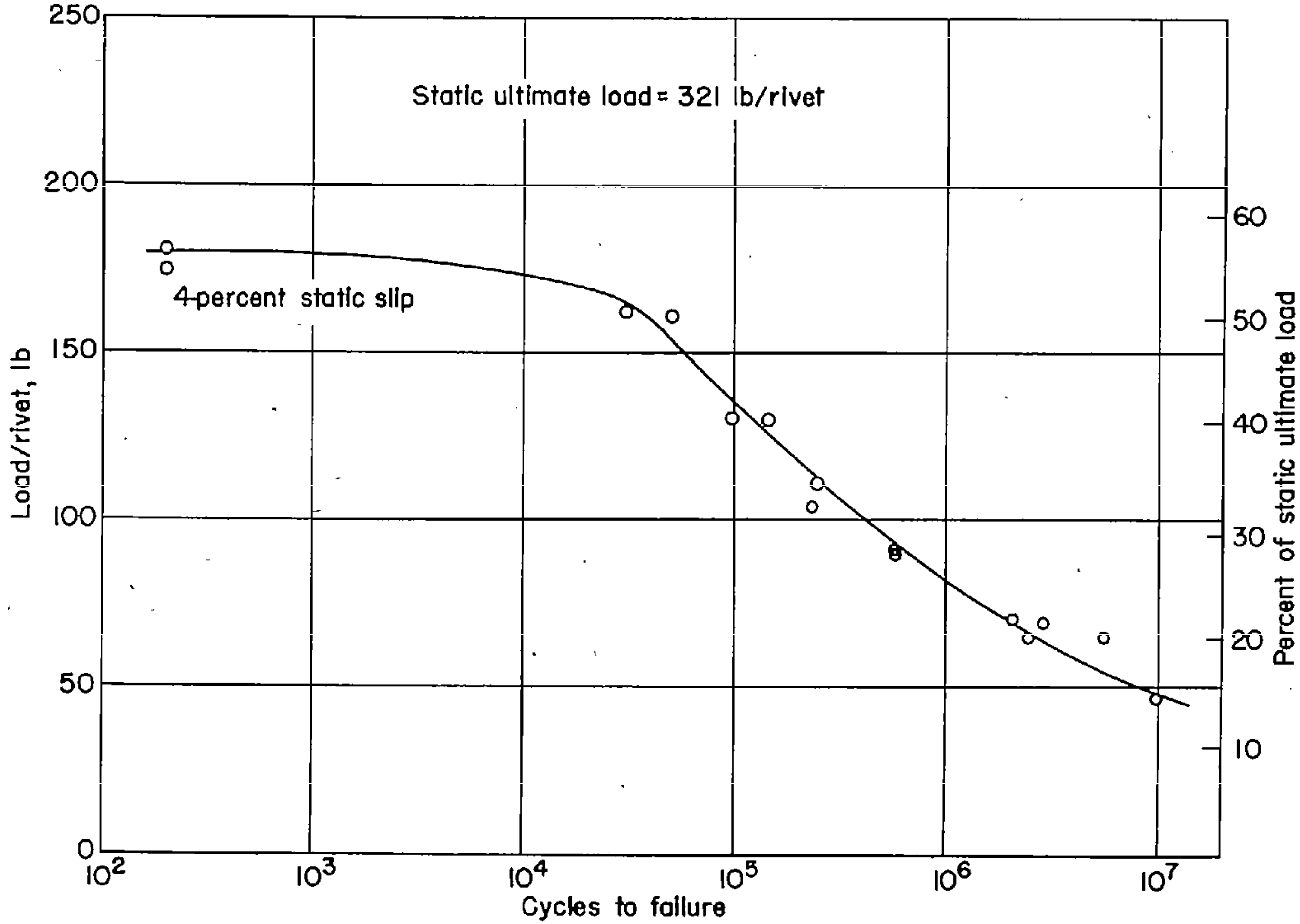
(e) 0.032-inch bare 24S-T3.

Figure 9.- Concluded.



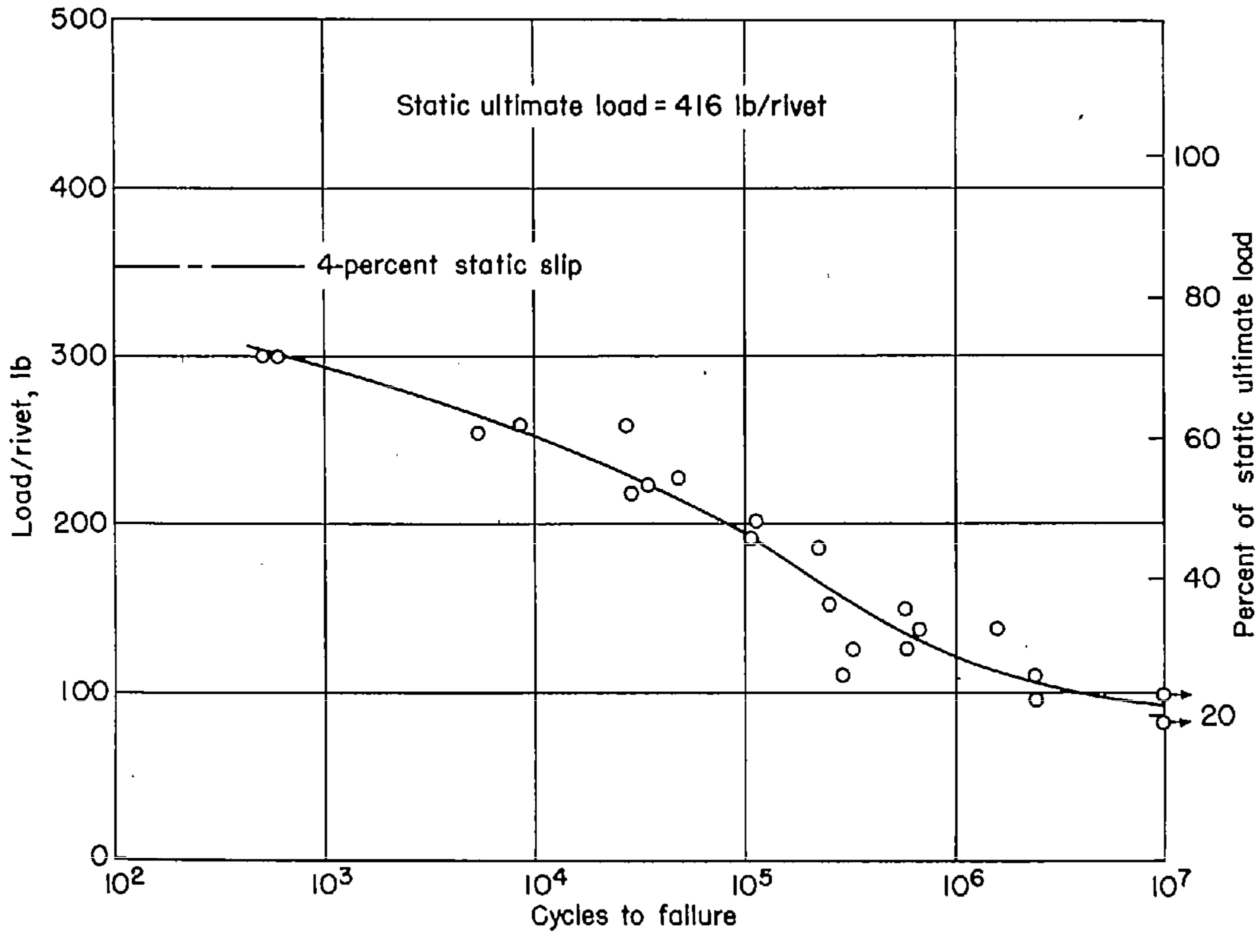
(d) 0.032-inch bare 75S-T6.

Figure 9.- Continued.



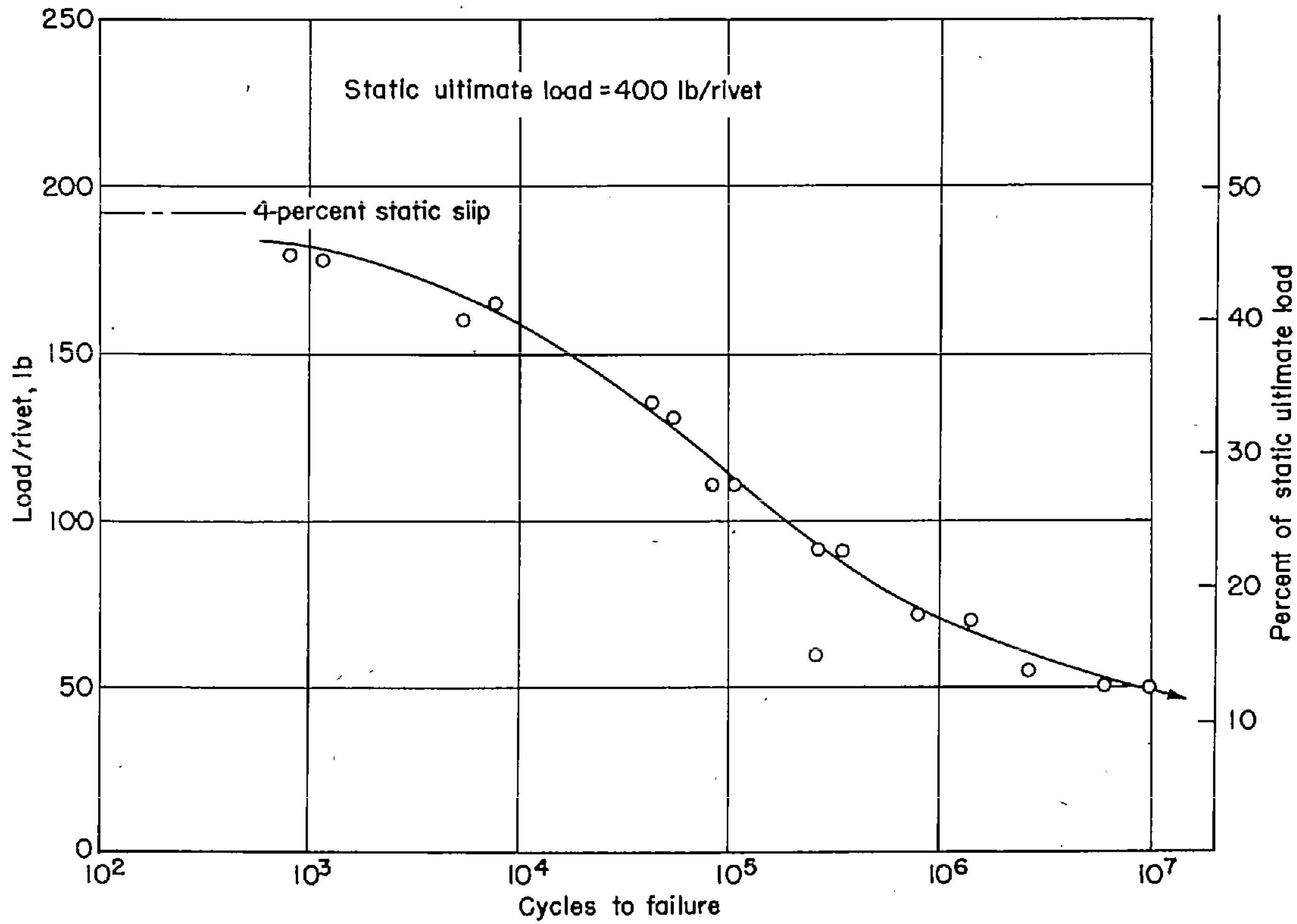
(c) 0.032-inch alclad 24S-T3.

Figure 9.- Continued.



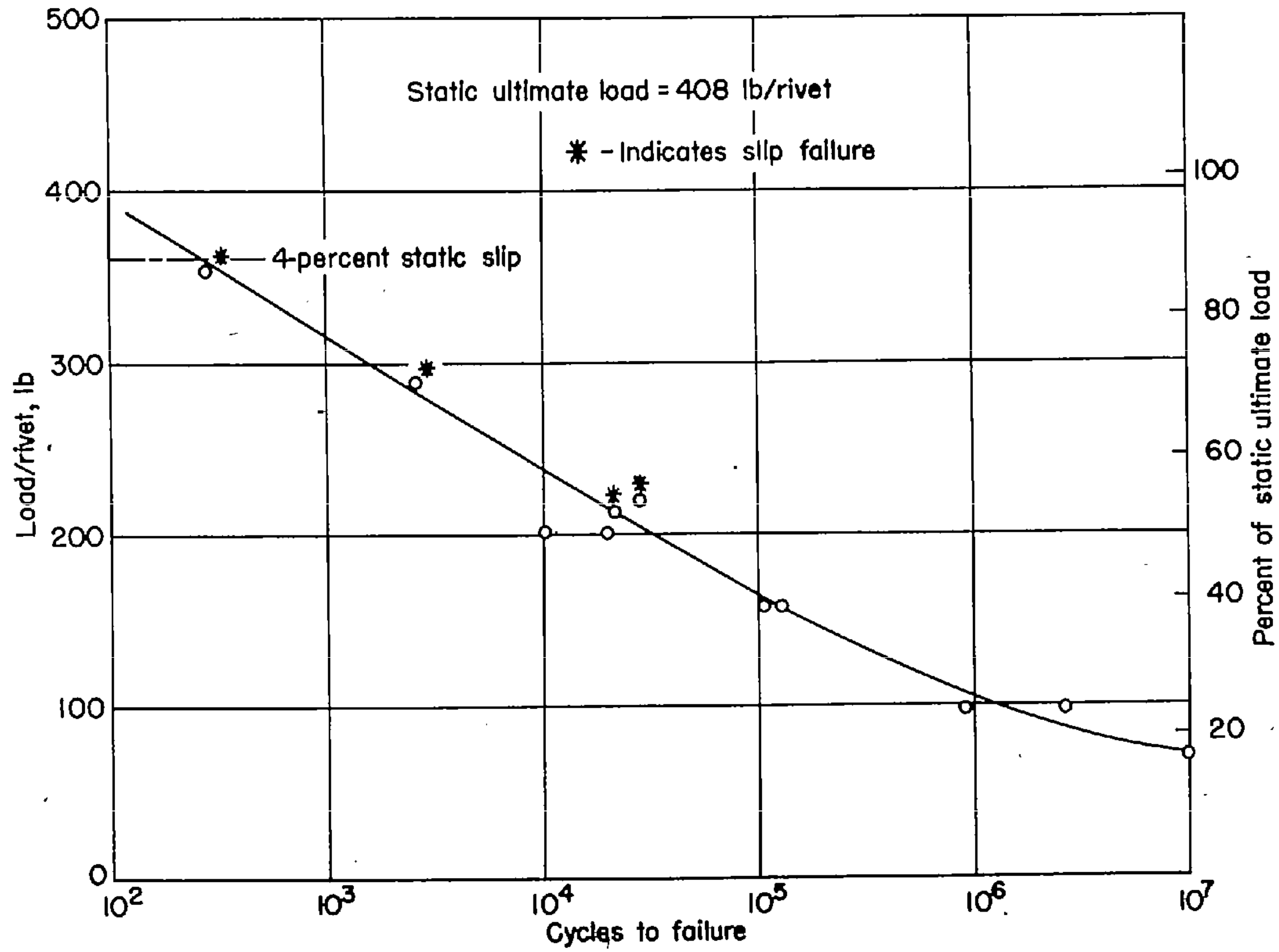
(b) 0.064-inch alclad 75S-T6.

Figure 9.- Continued.



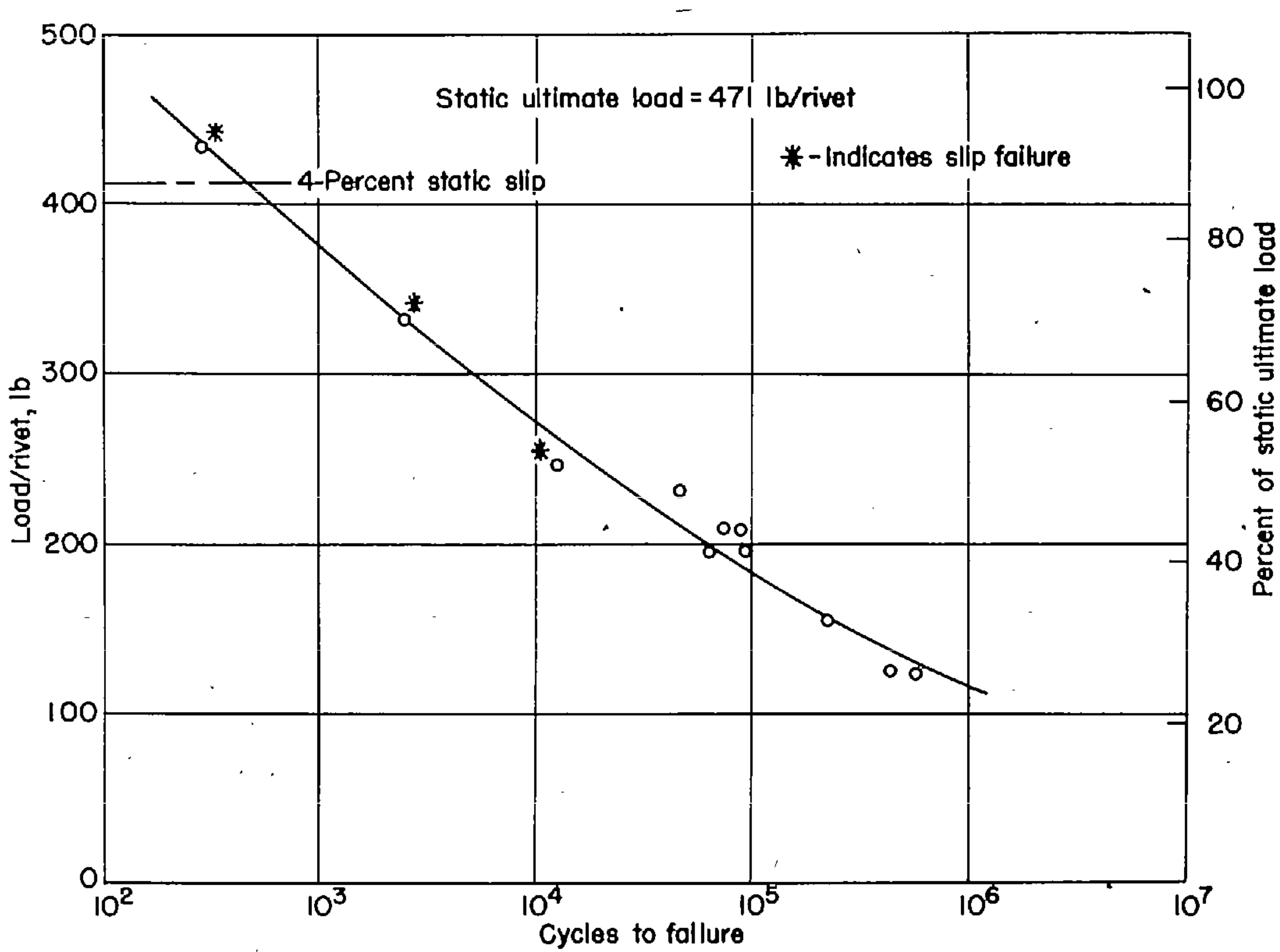
(a) 0.032-inch alclad 75S-T6.

Figure 9.- Curves of load per rivet against cycles to failure for machine-countersunk lap joints.



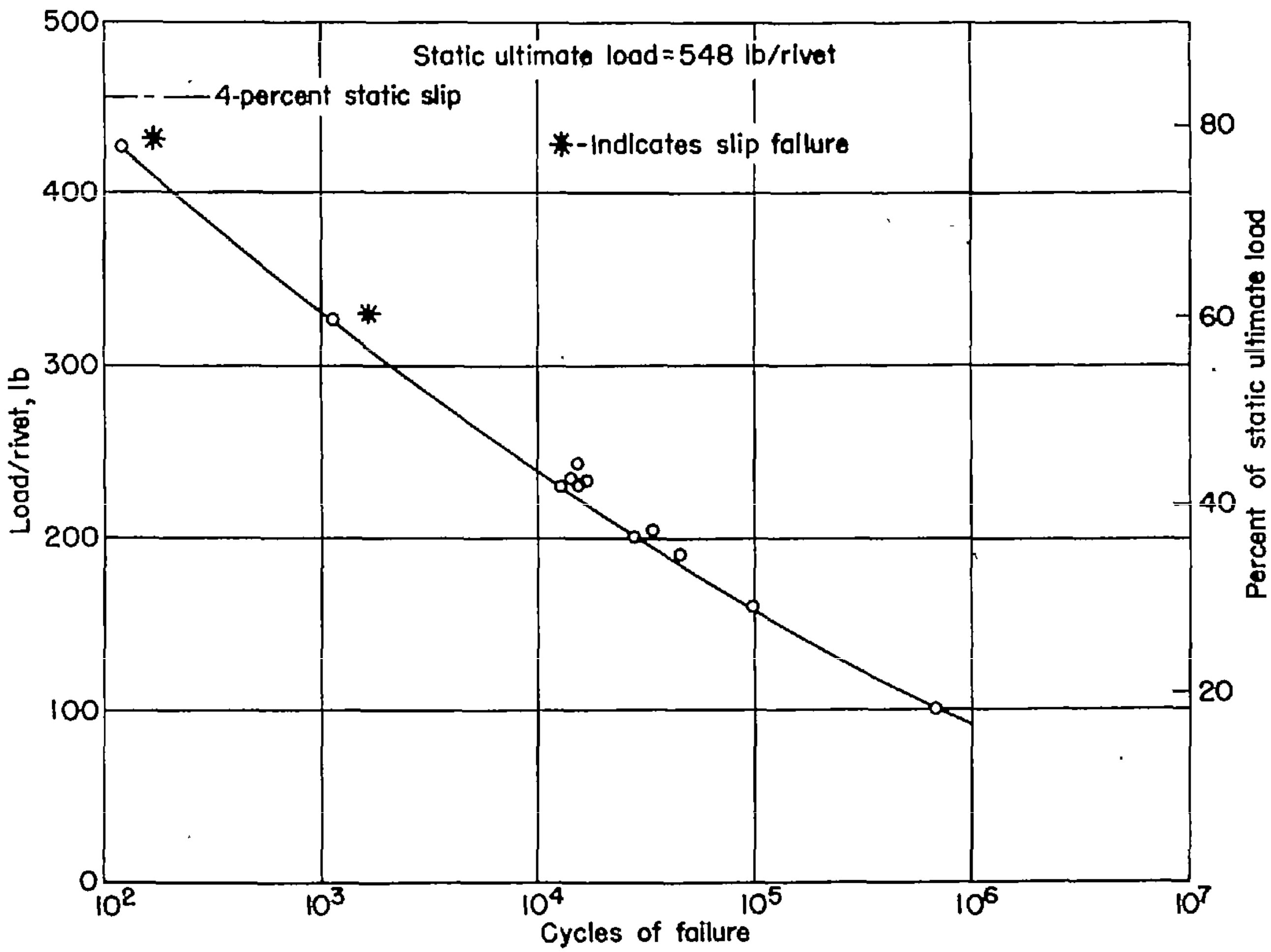
(d) 0.032-inch bare 24S-T3.

Figure 10.- Concluded.



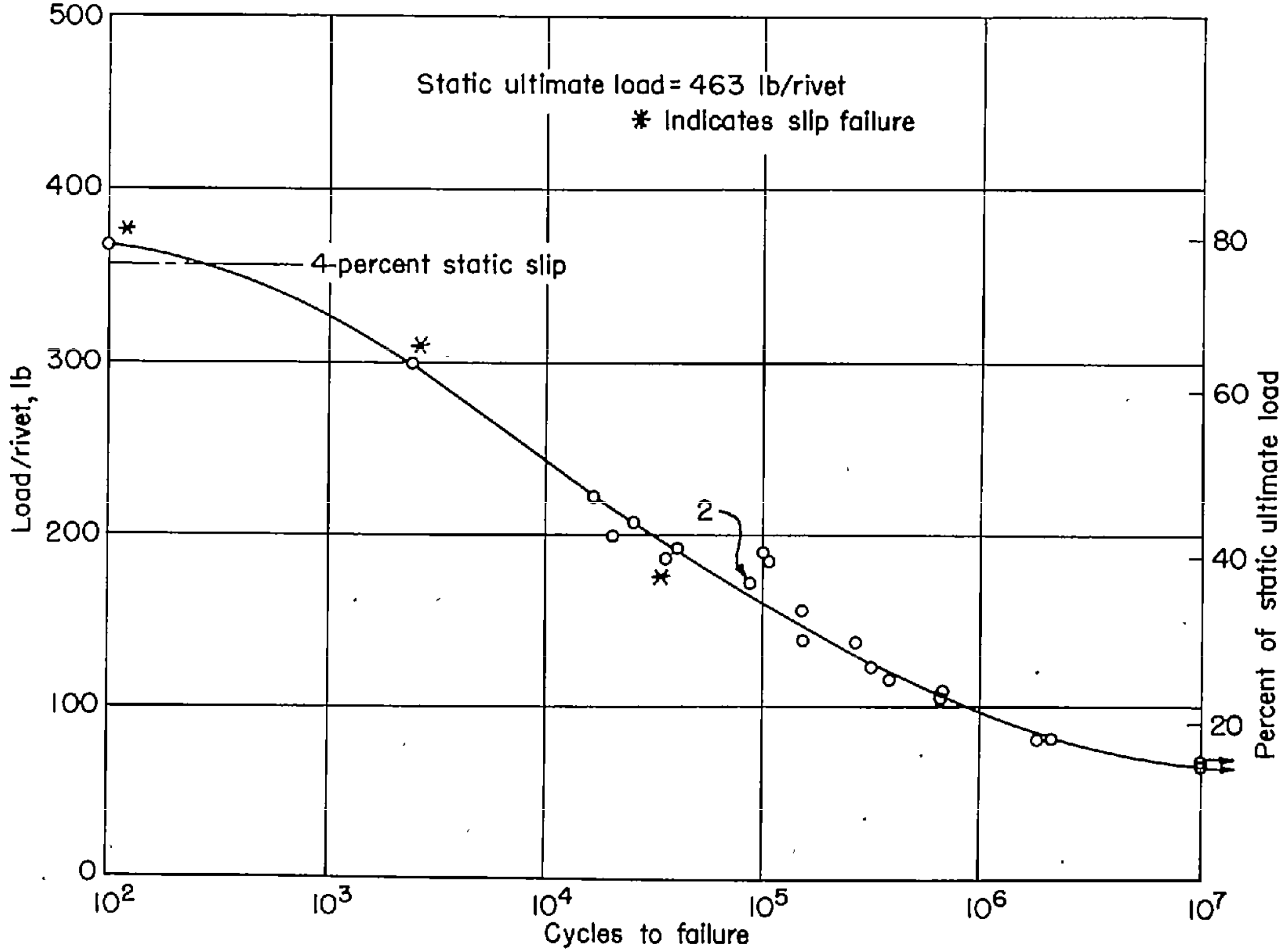
(c) 0.032-inch bare 75S-T6.

Figure 10.- Continued.



(b) 0.032-inch alclad 75S-T6.

Figure 10.- Continued.



(a) 0.032-inch alclad 24S-T3.

Figure 10.- Curves of load per rivet against cycles to failure for dimpled lap joints.

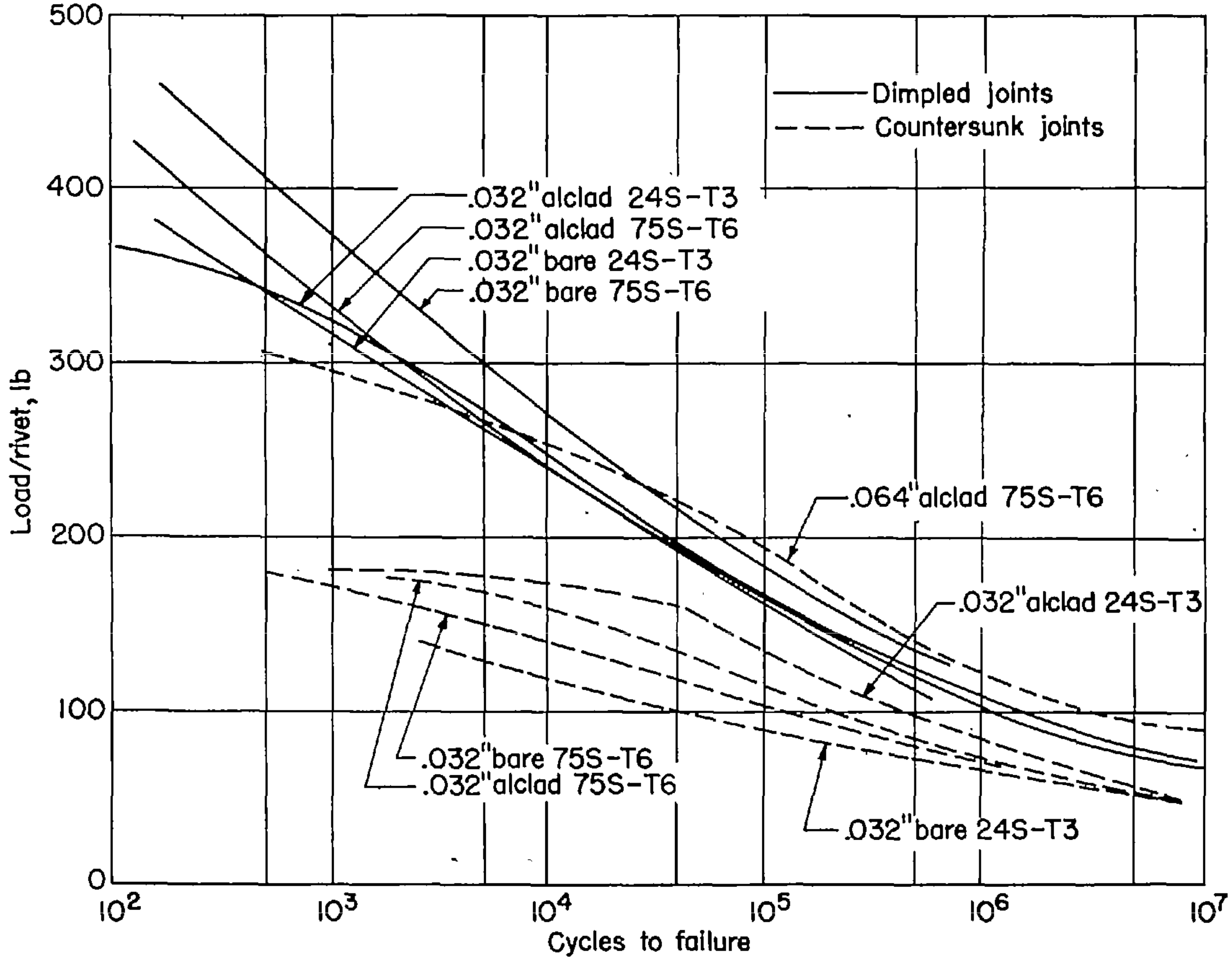
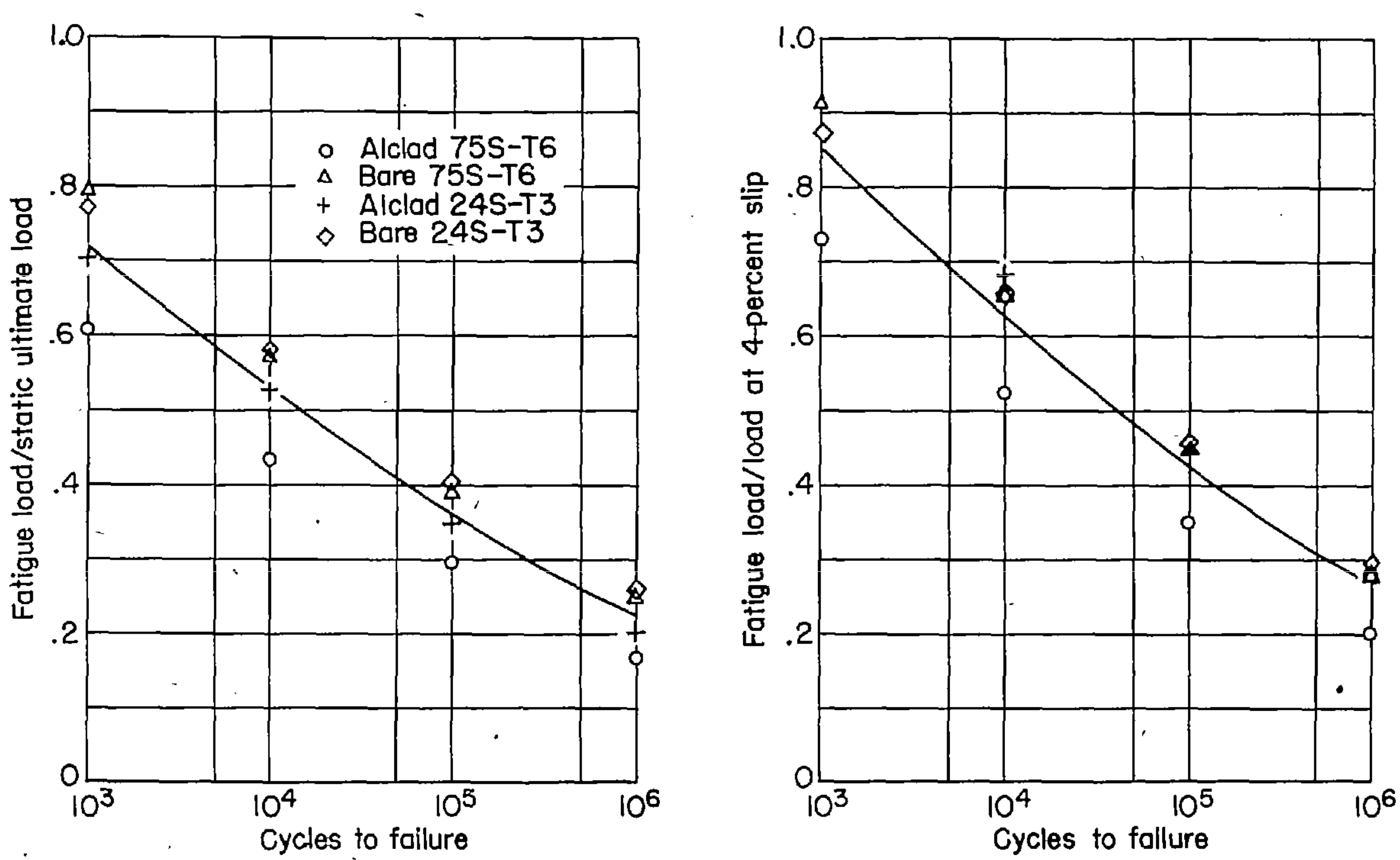
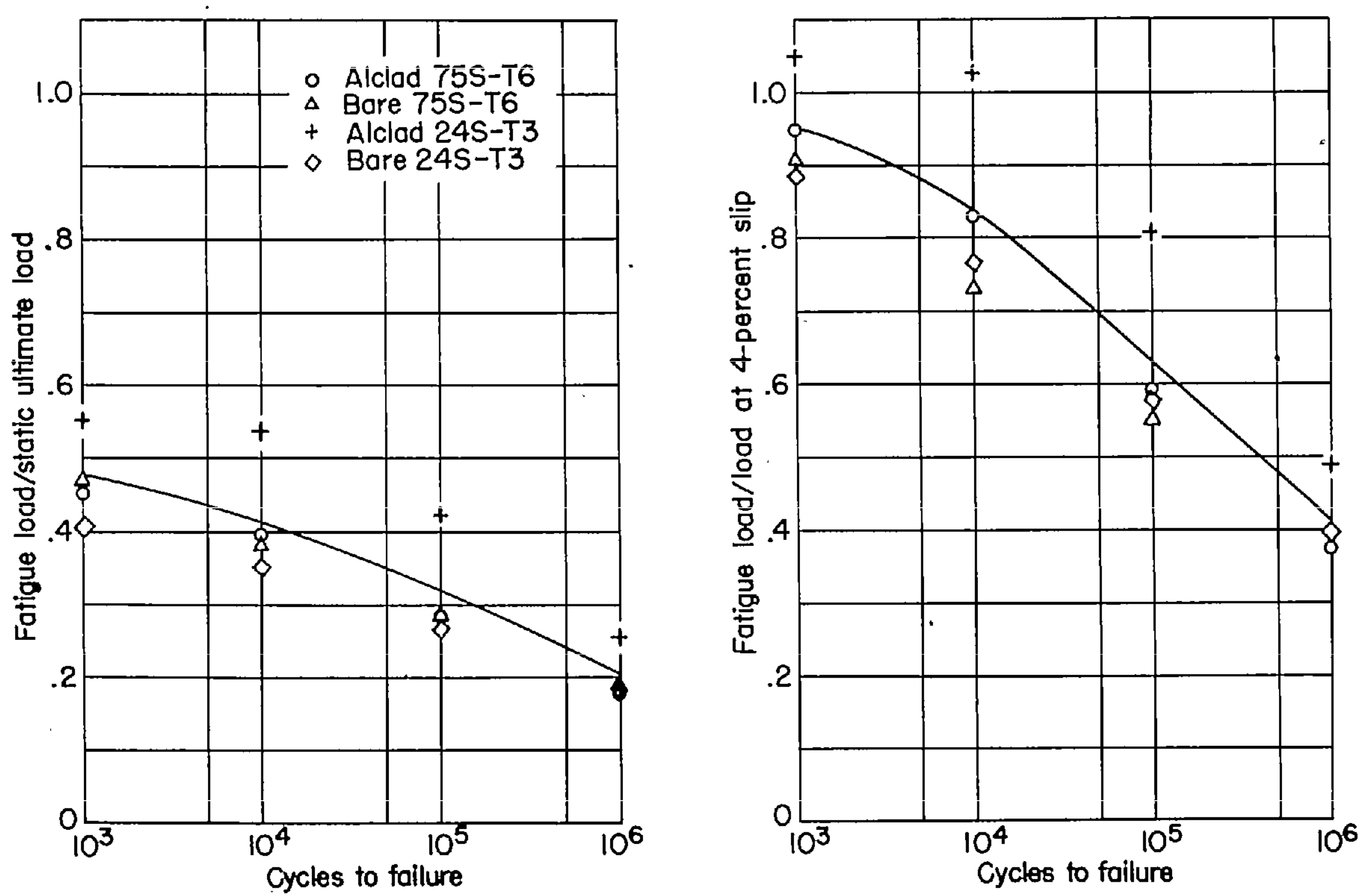


Figure 11.- Comparison of lap joints of different materials.



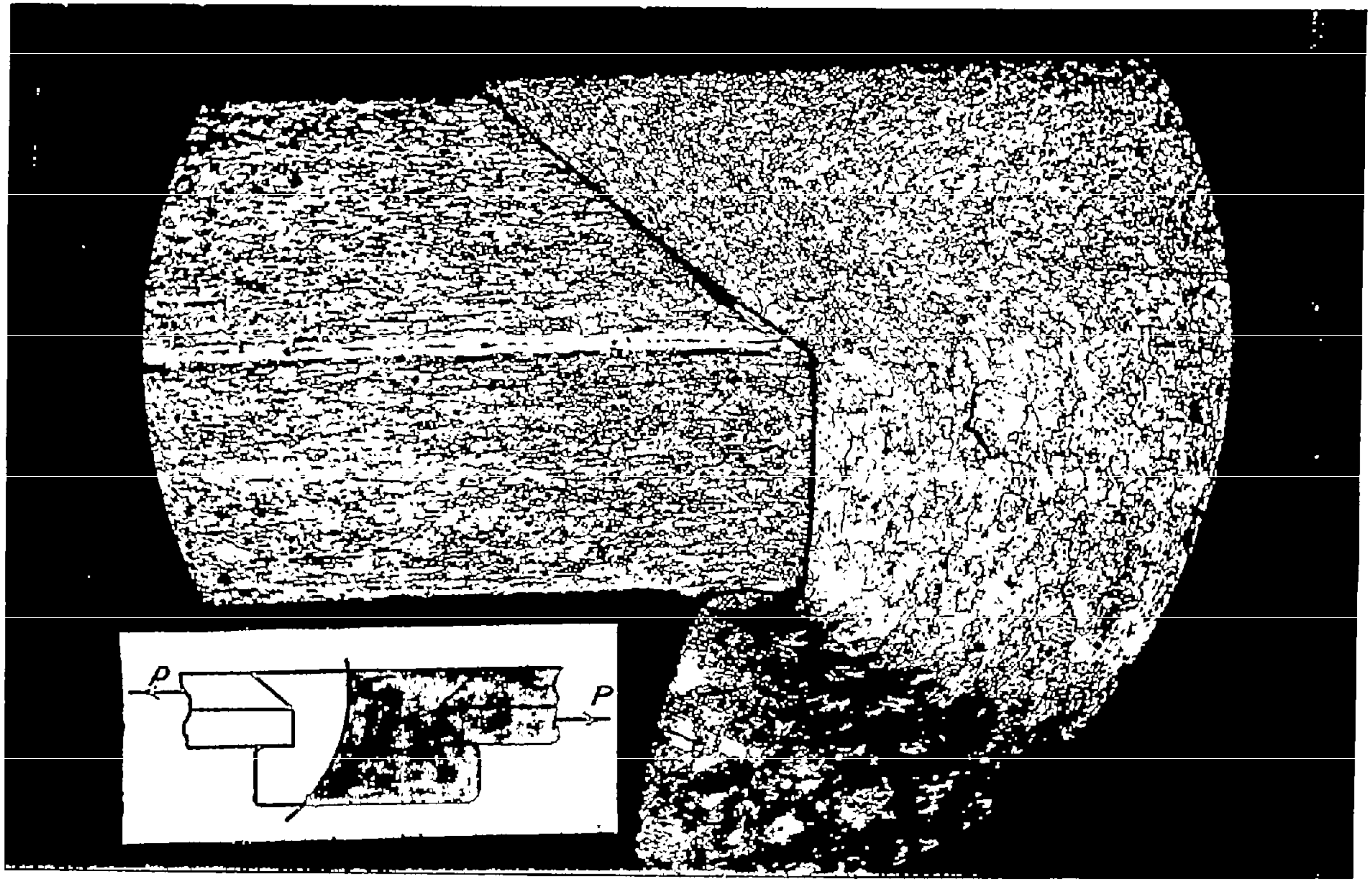
(b) Dimpled.

Figure 12.- Concluded.



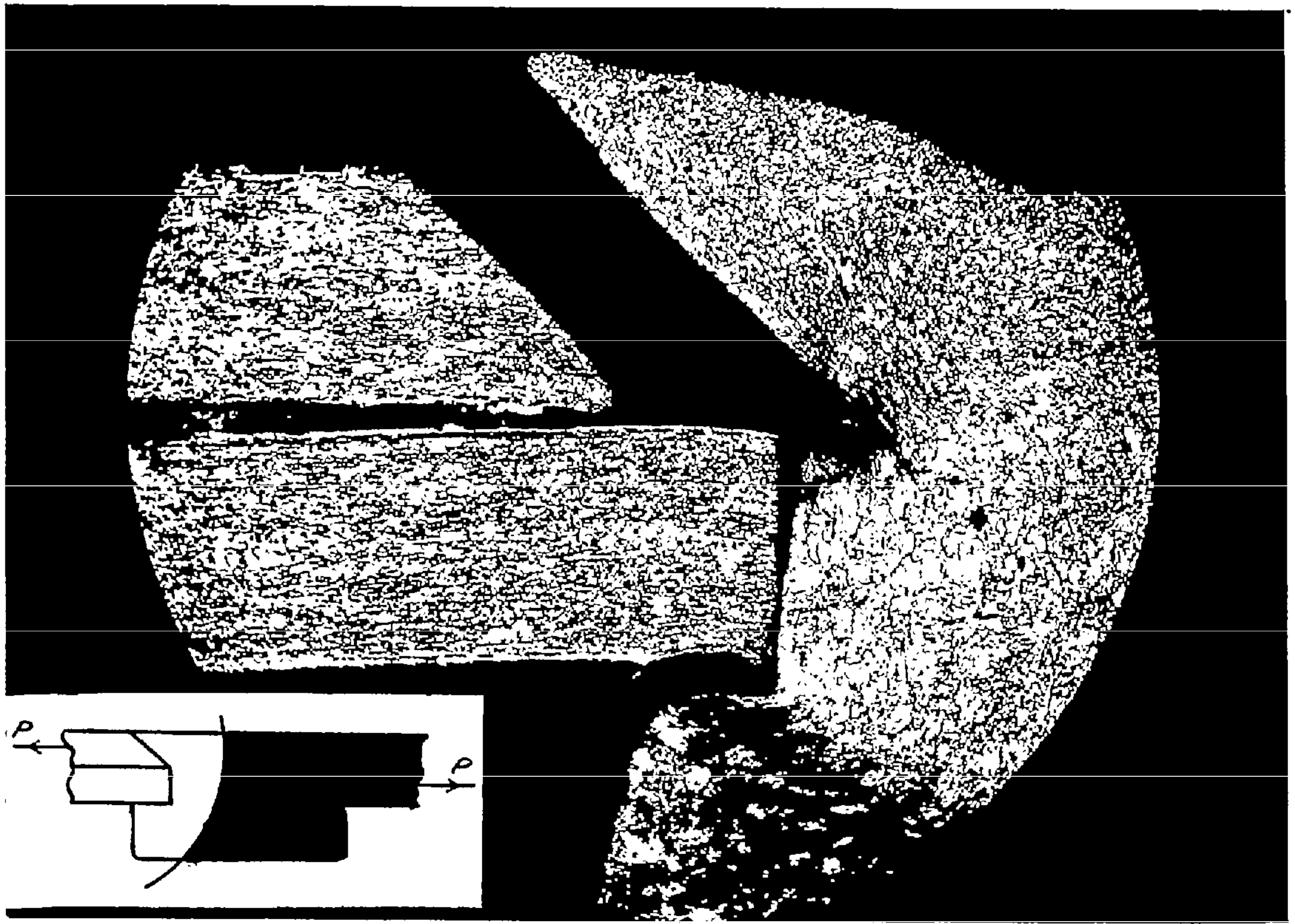
(a) Machine countersunk.

Figure 12.- Comparison of fatigue strength ratios of 0.032-inch lap joints.



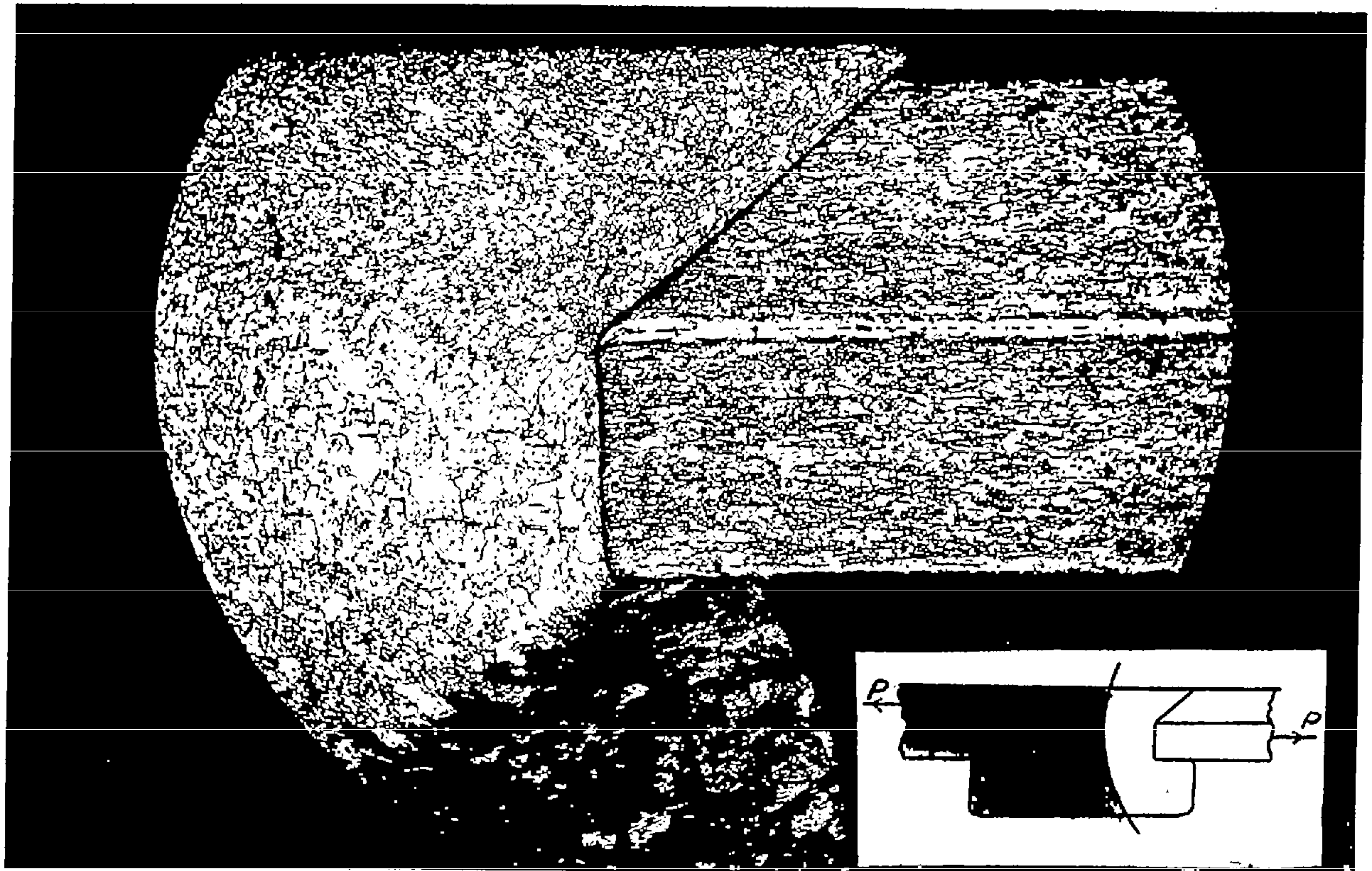
(a) Left side.

Figure 13.- Rivet before test. Lap joint in alclad 24S-T3 with machine-countersunk holes.



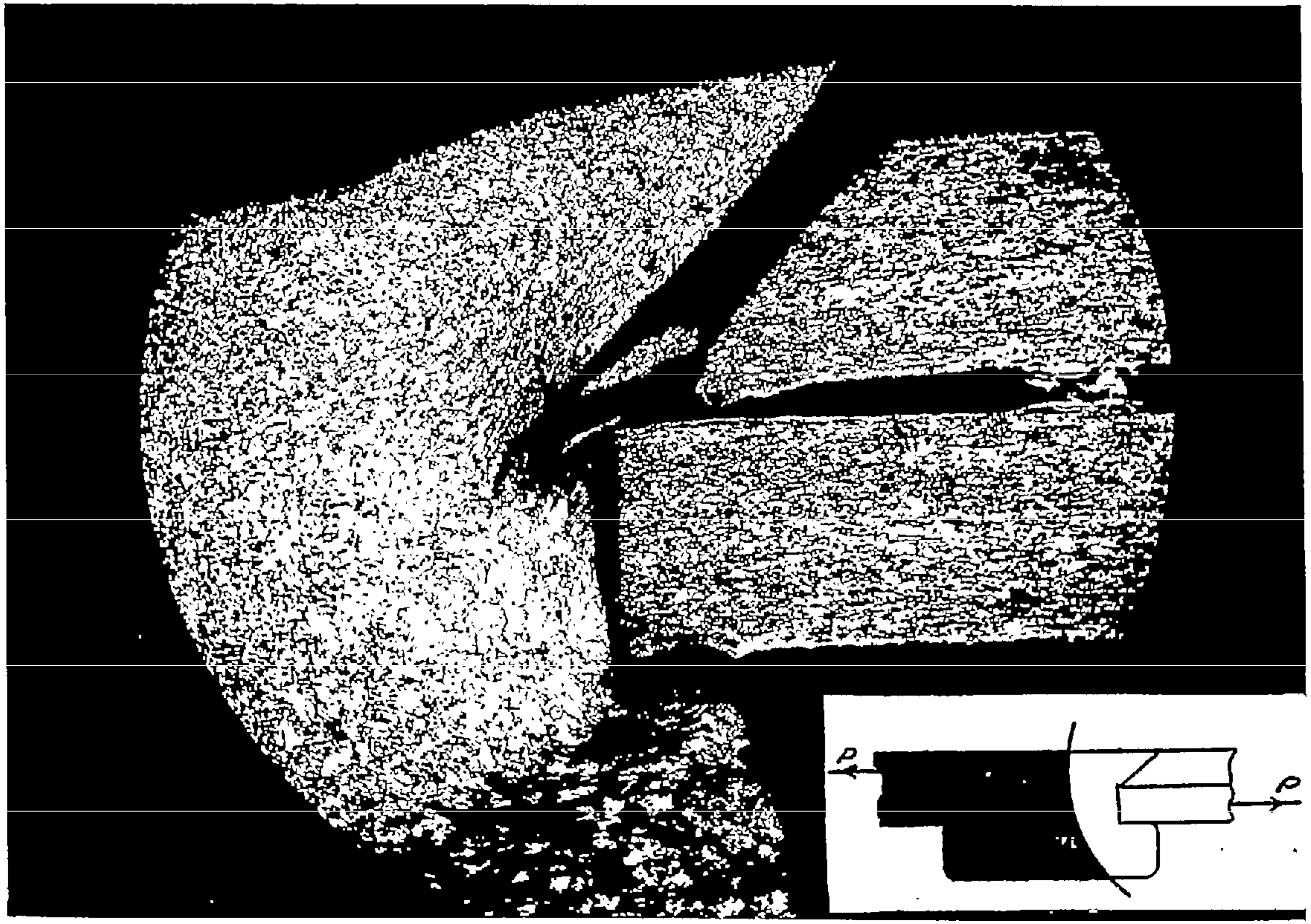
(a) Left side.

Figure 14.- Rivet after test. Lap joint in alclad 24S-T3 with machine-countersunk holes.



(b) Right side.

Figure 13.- Concluded.



(b) Right side.

Figure 14.- Concluded.

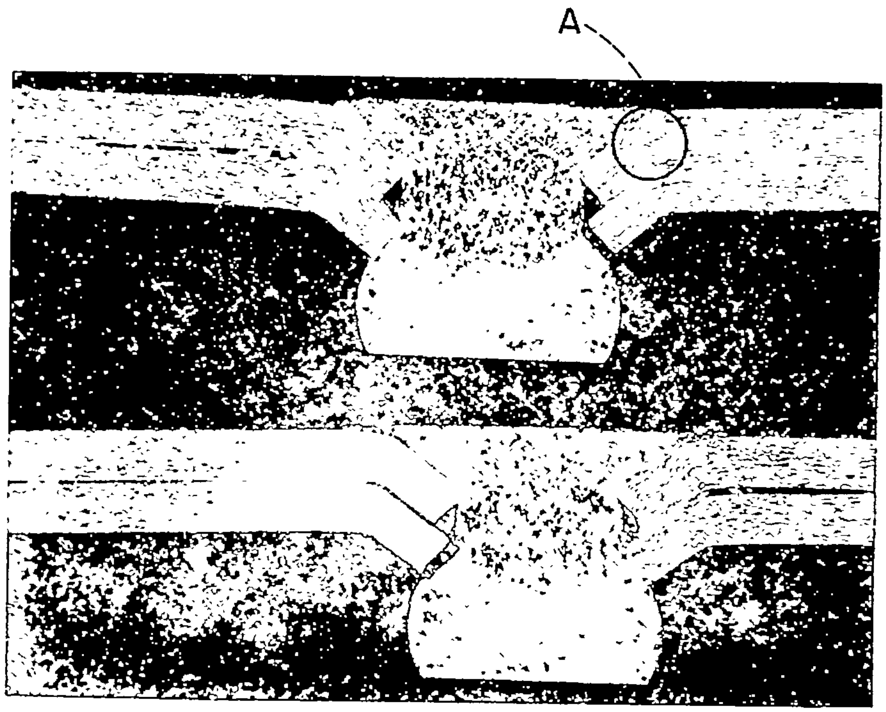


Figure 15.- Section of dimpled joints in 0.032-inch 75S-T6 aluminum-alloy sheet after fatigue failure. Cracks shown at A. X8.

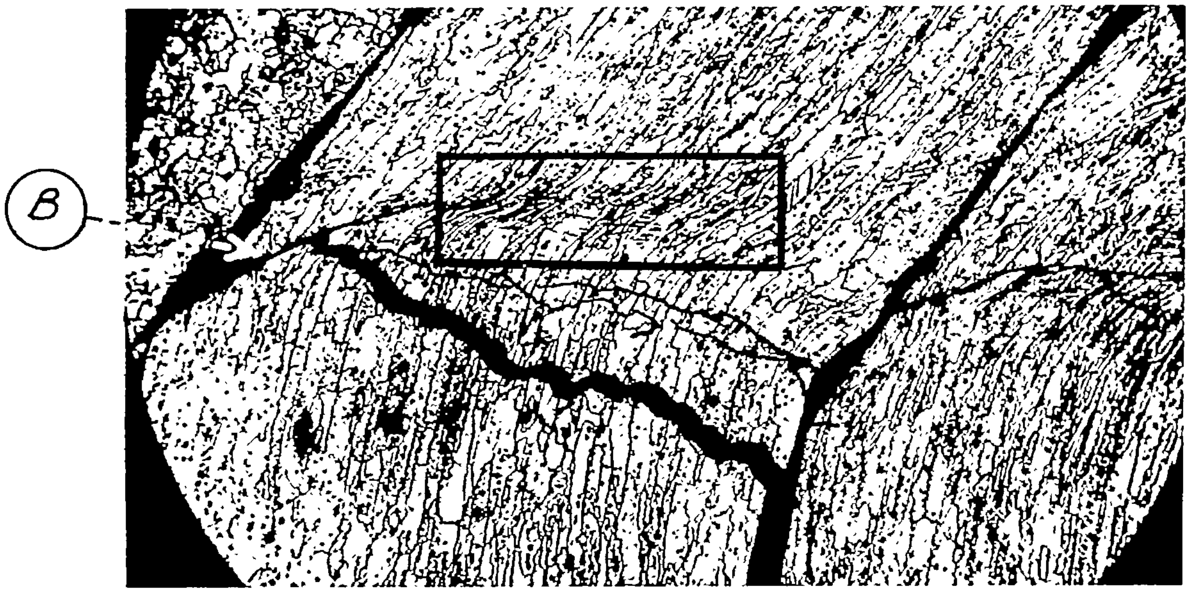


Figure 16.- Cracks at A in figure 15. Crack started at B, began to move through heavily cold-worked area (rectangular box), and changed direction probably because of higher stressing along line of eventual failure. X100.

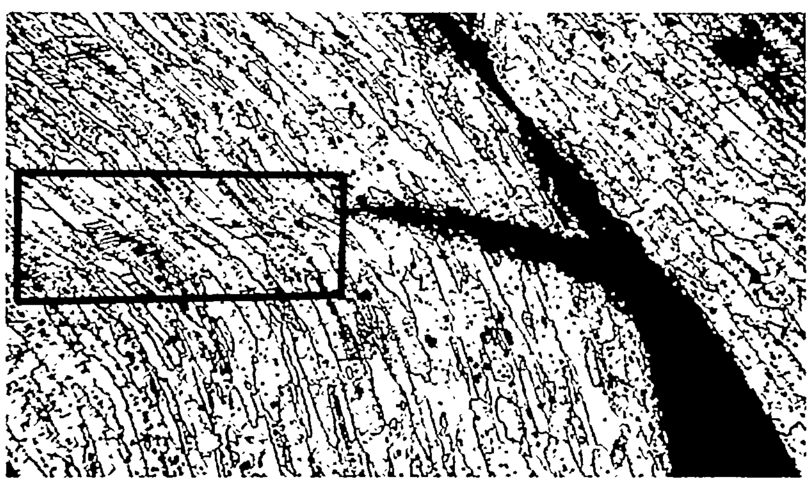


Figure 17.- Secondary crack on convex side of dimple in 75S-T6 alloy. Crack propagation through area of heavily cold-worked material (rectangular box). X100.

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